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THE HENRICI HARMONIC ANALYZER AND DEVICES FOR EXTENDING AND FACILITATING ITS USE.*

BY

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HARMONIC ANALYSIS.

THE harmonic method of analysis, based upon Fourier's Theorem, first published in "La Théorie Analytique de la Chaleur" (Paris, 1822), is of very great value in the investigation of many phenomena which can be represented by curves, and especially of wave motions which are represented by periodic curves. This theorem may be stated as follows: If any curve be given, having a wave-length l, the same curve can always be reproduced,

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and in one particular way only, by compounding simple harmonic curves of suitable amplitudes and phases, in general infinite in number, having the same axis and having wave-lengths of l, $\frac{1}{2}\,l$, $\frac{1}{3}\,l$, and successive aliquot parts of l. The given curve may have any arbitrary form whatever, including any number of straight portions, provided that the ordinate of the curve is always finite and that the projection on the axis of a point describing the curve moves always in the same direction.[1, 2] The practical significance of this theorem and the complete processes of harmonic analysis and synthesis have been explained in detail and graphically illustrated elsewhere by the author.[3, 4]

The mathematical expression for a curve, derived in accordance with Fourier's Theorem, consists of an infinite trigonometric series of sines and cosines, which may be stated as follows:

$$y=\frac{1}{l}\int_0^l y\,dx+\begin{cases}\left[\frac{2}{l}\int_0^l y\sin\frac{2\pi x}{l}\,dx\right]\sin\frac{2\pi x}{l}+\left[\frac{2}{l}\int_0^l y\sin\frac{4\pi x}{l}\,dx\right]\sin\frac{4\pi x}{l}+\cdots\\ \left[\frac{2}{l}\int_0^l y\cos\frac{2\pi x}{l}\,dx\right]\cos\frac{2\pi x}{l}+\left[\frac{2}{l}\int_0^l y\cos\frac{4\pi x}{l}\,dx\right]\cos\frac{4\pi x}{l}+\cdots\end{cases}\qquad \text{I}$$

in which y is the ordinate of the original complex curve at any point x on the base line, and l is the fundamental wave-length.

For the purposes of mathematical treatment it is convenient to express the abscissæ x in terms of angular measure, θ radians, with such a unit that the wave-length l equals 2π radians. The equation then has the form,

$$y=\frac{1}{2\pi}\int_0^{2\pi} y\,d\theta+\begin{cases}\left[\frac{1}{\pi}\int_0^{2\pi} y\sin\theta\,d\theta\right]\sin\theta+\left[\frac{1}{\pi}\int_0^{2\pi} y\sin 2\theta\,d\theta\right]\sin 2\theta+\cdots\\ \left[\frac{1}{\pi}\int_0^{2\pi} y\cos\theta\,d\theta\right]\cos\theta+\left[\frac{1}{\pi}\int_0^{2\pi} y\cos 2\theta\,d\theta\right]\cos 2\theta+\cdots\end{cases}\qquad \text{II}$$

If the first term is represented by a_0, and the coefficients of the sine and cosine terms, the quantities in square brackets are represented by a_1, b_1, a_2, etc., the equation will have the following symbolic form of simpler appearance:

$$y=a_0+\begin{cases}a_1\sin\theta+a_2\sin 2\theta+\ldots\\ b_1\cos\theta+b_2\cos 2\theta+\ldots\end{cases}\qquad \text{III}$$

The term a_0 is a constant and is equal to the distance from the line assumed as a base to the true axis of the curve; if the base coincides with the axis, $a_0=0$, and this term does not appear in the equation of the curve. This term has no relation to the form or

significance of the curve, and usually its value is not required; it may be determined, however, by means of an ordinary planimeter, as described in the reference.[3]

The other terms of the equation occur in pairs, as $a_1 \sin\theta$, $b_1 \cos\theta$, etc., and each term, whether a sine or a cosine, represents a simple harmonic curve. The successive terms of the series of sines and of cosines repeat themselves with frequencies of 1, 2, 3, etc., which means that the curves have wave-lengths in the proportion of $1 : \frac{1}{2} : \frac{1}{3}$: etc.; such a succession of terms is said to form a *harmonic* series.

The coefficients of the various terms, the quantities in square brackets in equation I, which are represented by a_1, b_1, a_2, etc., in equation III, have the following general form, n being the *order* of the term and l the wave-length: [1, 2]

$$\frac{2}{l}\int_0^l y \sin\frac{2n\pi x}{l}\,dx.$$

Each coefficient is a number or factor indicating how much of the corresponding simple sine or cosine curve enters into the composite; that is, it shows the height or *amplitude* of the simple component.

The process of *analyzing a curve* consists of finding the particular numerical values of the coefficients of the Fourier equation so that it shall represent the curve. In general the number of terms required is indefinitely great, or even infinite, but in many instances a finite number of terms is sufficient. Whenever certain of the simple curves are not required, the corresponding coefficients are said to have the value zero, and their terms do not appear in the equation of the curve. In the study of sound waves the number of terms involved seldom exceeds thirty and often does not exceed ten. Fourier showed how the numerical values of the coefficients may be calculated, but the process is very long and tedious, requiring perhaps several days' work for a single curve. The great importance of harmonic analysis has caused the development of many methods, numerical, graphical, and mechanical, for facilitating the calculations.[3] The main part of each coefficient is a definite integral which is of the nature of an area, and various area-integrating machines, known in their simpler forms as *planimeters*, may be adapted to the evaluation of these coefficients. A complete apparatus arranged for mechanically deriving the Fourier equation of a curve is called a *harmonic analyzer*.

Perhaps the most convenient and precise harmonic analyzer yet devised is that of Henrici. An instrument of this type has been in use by the author since 1908 in the study of sound waves, and with it several thousand curves have been analyzed. The experience thus gained has led to the development of various instruments and methods for facilitating the analytical work, both with this particular form of analyzer and in general. It is the purpose of this paper to describe these devices.

HENRICI'S HARMONIC ANALYZER FOR TEN COMPONENTS.

The harmonic analyzer devised by Prof. O. Henrici, of London, is based upon the rolling sphere integrator, and its theory was first published in 1894.[5] These analyzers have been developed and mechanically perfected by Mr. G. Coradi, of Zurich; and, as constructed by him, they are not only of beautiful workmanship, but they are also calculating machines of high precision. An analyzer of this type, with five integrating apparatus, is shown in Fig. 1. The theory of the Henrici analyzer will be stated very briefly.

The general expressions for the coefficients of the sine and cosine terms of the Fourier equation, form II (represented by a_1, b_1, etc., in form III), integrated by parts, give the following equations, n being the order of the term:

$$a_n = \frac{1}{\pi}\int_o^{2\pi} y \sin n\theta d\vartheta$$

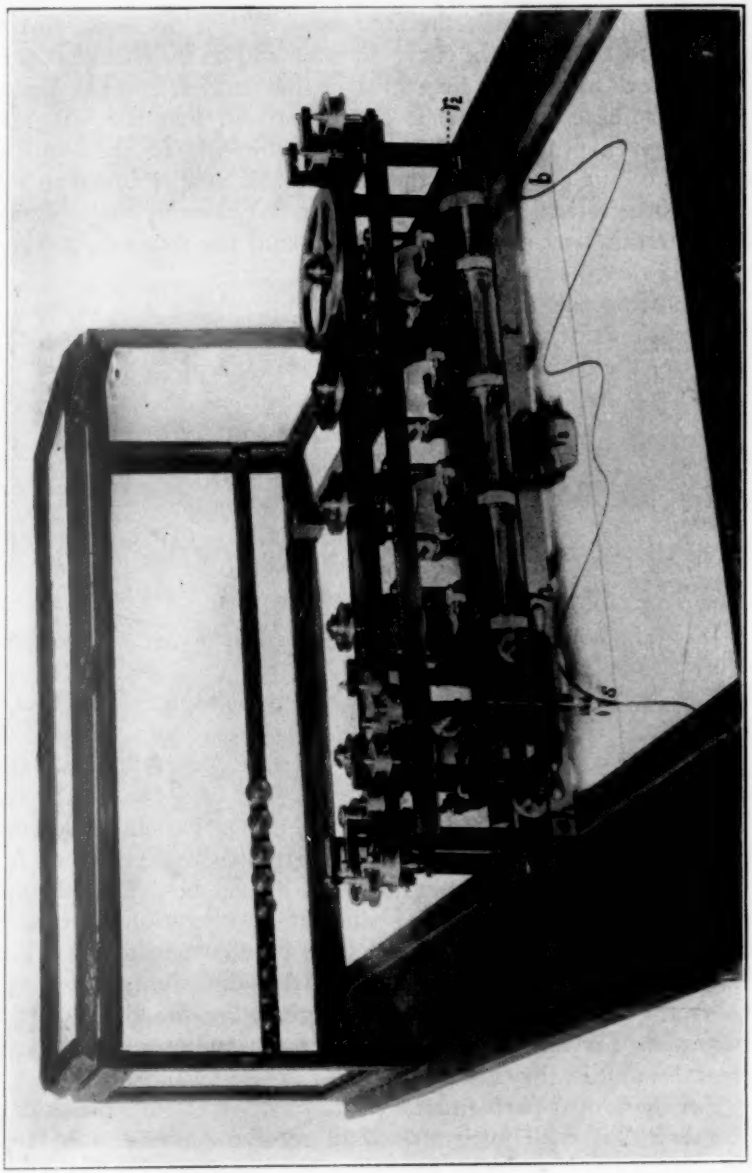
$$= \left[-\frac{1}{n\pi} y \cos n\theta \right]_o^{2\pi} + \frac{1}{n\pi}\int_o^{2\pi} \cos n\theta dy,$$

$$b_n = \frac{1}{\pi}\int_o^{2\pi} y \cos n\theta d\theta$$

$$= \left[\frac{1}{n\pi} y \sin n\theta \right]_o^{2\pi} - \frac{1}{n\pi}\int_o^{2\pi} \sin n\theta dy$$

If the curve is continuous, and if the initial and final values of y are equal, the terms in square brackets disappear. Nearly all the curves representing physical phenomena satisfy these conditions. If the curve has a discontinuity, it is made continuous

FIG. 1.



Henrici harmonic analyzer.

for purposes of analysis by joining the two points of discontinuity by a straight line; and if the final value of y is not equal to the initial value, that is, if the curve does not end on the base line, it is brought back to the base by a straight line parallel to the ordinate y. Under these conditions it can be proved that the integrals already given properly measure the coefficients of the Fourier equation of the curve. Further, if the base line is added to the path of integration, nothing is added to the value of the integral, since for this part of the path $dy = 0$, and the integral is taken around a closed curve.

Therefore the *Henrici integrals*, which define the values of the coefficients of the Fourier equation of the curve, have for the sine terms the form, n being the order of the term,

$$a_n = \frac{1}{n\pi} \int_{\theta=0}^{\theta=2\pi} \cos n\theta dy,$$

and for the cosine terms the form,

$$b_n = -\frac{1}{n\pi} \int_{\theta=0}^{\theta=2\pi} \sin n\theta dy.$$

It will be noticed that the coefficients of the sine terms contain cosine integrals, and *vice versa*.

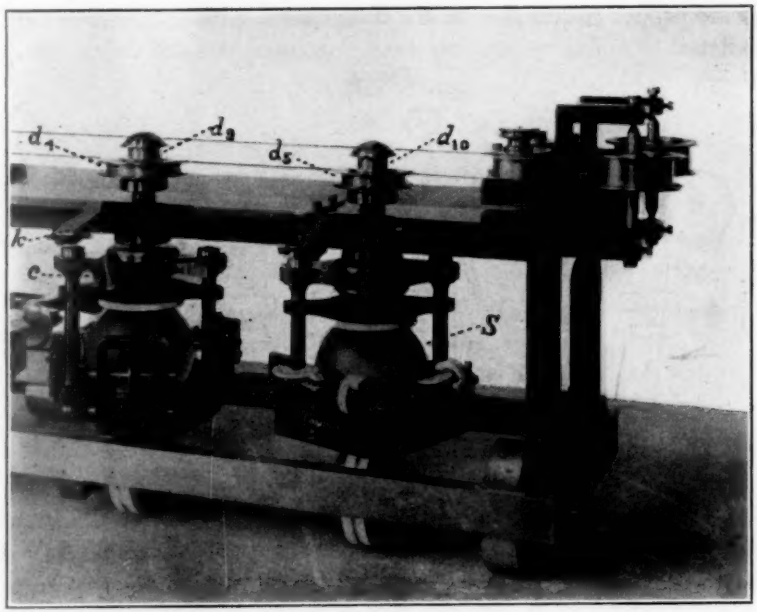
For the evaluation of any a coefficient, as the nth, it is necessary that each element of amplitude dy of the original curve shall be multiplied by the instantaneous value of cos $n\theta$ and that the whole be integrated between the limits $\theta = 0$ and $\theta = 2\pi$; for the b coefficients the operation is the same, except that the resolving factor is sin $n\theta$. The analyzer, then, is an integrating machine for evaluating these special integrals, and it may be arranged with one or more integrators, each of which at one operation determines one pair of integrals defining the term of a certain order. The integrations for the terms of various orders differ only as regards the factor n. The actual readings given by the dials of the integrators for any term are n times the values of the above integrals; that is, they are na_n and nb_n.

For the proper performance of its function of integration it is necessary that each integrator shall receive the effects of two rectangular motions which are related to the area of the curve in certain particular ways as required by the development of

Fourier's theorem. One of these movements is secured by the rolling of the instrument as a whole, back and forth parallel to itself, while the second is obtained from the movement of a carriage along a transverse track.

The analyzer is supported by three rollers, r_1, r_2, and r_3, Fig. 1. The curve to be analyzed, which must be drawn to a specified scale, is placed underneath, and is adjusted so that its axis (or base) is parallel to the track t; this condition may be determined by

FIG. 2.



The rolling sphere integrator.

inspection or by moving the carriage with the stylus s along the track and adjusting the curve until the stylus traces the given line. If no base line is given, any line touching the crests or troughs of two consecutive waves, or any parallel to such a line, may be used. The stylus is placed over the initial point of the curve, as shown; the stylus is adjustable in a transverse slot to facilitate this setting. The initial point may be chosen at convenience, since the analyses of a curve made from different starting points will (when fully reduced) differ only in the phases of the components. The

handles *h* are grasped with the fingers and the stylus is caused to trace one exact wave-length of the curve, when it will again be on the base line, at the point *b;* the stylus is returned to the starting point *s,* along the assumed base line, completing the integration around a closed curve. The latter operation theoretically adds nothing to the value of the integral, while it eliminates errors which would be produced if the axes on which the integrators revolve do not pass through the centre of the axle *a*. The tracing of the curve will have required a combination of the two specified rectangular movements, and the manner of communicating these in the proper proportion to the integrators will be now described in detail.

FIG. 3.

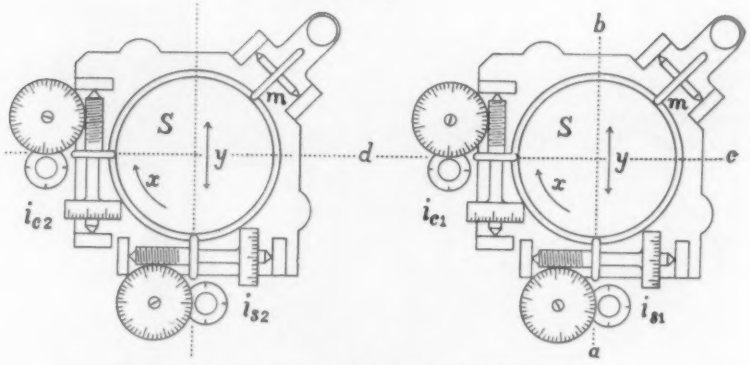


Diagram of two rolling sphere integrators in initial positions.

The rolling sphere integrator has for its essential parts a sphere of glass, *S,* Fig. 2, which when in use rests upon a celluloid roller underneath it at what may be called the south pole, and two integrating cylinders, i_{s_1} and i_{c_1}, Fig. 3, which rest against the equatorial circumference of the sphere and, while revolving around the sphere, always touch it at points 90 degrees apart. A third roller, *m,* holds the sphere against the integrating wheels with a spring pressure. When not in use, each sphere may be lifted from all the rollers and be held securely between celluloid clamping rings. In this condition the integrating cylinders are free to move, and each may be set so that its dials indicate zero, preparatory to the operation of tracing a curve.

The rollers r_1 and r_2, Fig. 1, and the five celluloid rollers underneath the spheres are all rigidly attached to the same axle *a;* the

celluloid rollers, being smaller than the others, do not touch the paper.

As the curve is traced the machine rolls backward and forward, parallel to itself, the five spheres are *all rotated* by the *same amount,* and in the *same direction,* the direction of the amplitude of the curve, as indicated by the arrow y, Fig. 3. The amount of this rotation is always proportional to the amplitude y of the complex curve, and, therefore, at *each point* in the tracing, it is proportional to the instantaneous sum of the separate component amplitudes of the simple component curves.

The integrating cylinders i_s are for evaluating the sine coefficients and i_c for the cosines. Each pair of cylinders is attached

FIG. 4.

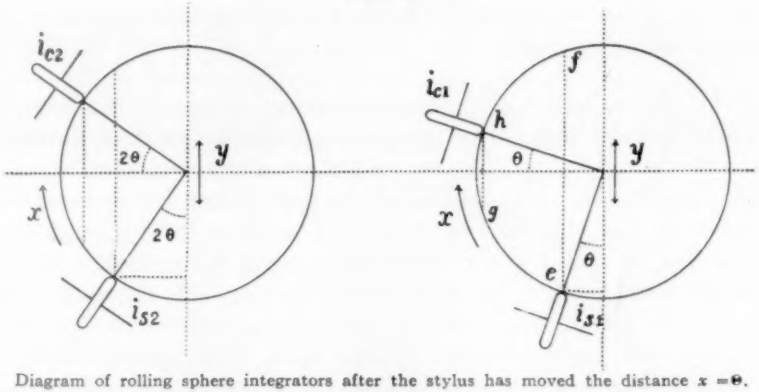


Diagram of rolling sphere integrators after the stylus has moved the distance $x = \theta$.

to a light frame which surrounds the equatorial region of the sphere, Figs. 2 and 3; the frame is supported from above and is capable of rotation independently of the sphere, on an axis in the prolongation of the north polar axis, as indicated by the arrows x. The initial or zero positions of the cylinders are shown in Fig. 1 and 3, the settings for which are facilitated by clamping screws c and spring stops k, Fig. 2. In this position $\theta = 0$, and when the instrument rolls in amplitude the sphere rolls in the plane ab and the integrating cylinder i_{s_1} records a rotation proportional to $dy \cos \theta$, and i_{c_1}, which touches the sphere at a point on the axis of rotation cd, has a rotation proportional to $dy \sin \theta$; that is, it is not rotated at all (for $\theta = 0$, $\cos \theta = 1$, and $\sin \theta = 0$).

When the stylus, in tracing the curve, has moved in the direction of the x axis by an amount equal to θ, the integrating cylinders

for the first component must be revolved (as described later) around the first sphere through an angle θ, Fig. 4, the integrators for the second component must revolve through an angle 2θ, and for any higher component the cylinders must be revolved through an angle $n\theta$. In the position shown in Fig. 4 the integrator i_{s_1}, which has moved through the angle θ, now touches the sphere on the circumference of a circle of diameter ef, and as the sphere rolls in amplitude by the amount dy, the cylinder receives a rotation proportional to $dy \cos \theta$; the integrator i_{c_1} touches the sphere on the circumference of the circle gh and it is rotated by an amount proportional to $dy \sin \theta$. The integrators i_{s_2} and i_{c_2} have at the same instant been revolved through the angle 2θ and they receive rotations proportional to $dy \cos 2\theta$ and $dy \sin 2\theta$, respectively. The integrators arranged for terms of other orders operate in a corresponding manner.

For the evaluation of the first component of a curve, the fundamental, the sine and cosine integrating cylinders must be carried around the sphere *exactly* one revolution while the stylus traces one fundamental wave-length of the curve, and for the second component the cylinders must revolve twice in the fundamental wave-length, and for the third component the cylinders must revolve three times in the same interval, etc. This revolution of the cylinders is accomplished by attaching a wire to the carriage of the stylus, which passes around fixed guide pulleys and is wrapped once around suitable disks, d_1, d_2, etc., Figs. 2 and 5, attached to the upper parts of the spindles which support the frames of the cylinders. One integrator may be used for evaluating any number of terms (one at a time) by supplying a series of disks suitable for turning the apparatus once, twice, three times, and so on, while the stylus traces the fundamental wave-length. Several integrators may be used simultaneously, the disks being of such diameters that the cylinders of the successive apparatus are revolved one, two, three, four, and five times, etc. The instrument being described, having five integrators, gives five pairs of coefficients with one tracing. Two disks are attached to each integrator, so that after one tracing the wire may be slackened and be removed from the lower series of disks d_4 and d_5, Fig. 2, and be wrapped around the upper series, d_9 and d_{10}, causing the integrators to revolve six, seven, eight, nine, and ten times, respec-

tively, for one wave-length, so that with two tracings ten pairs of coefficients are determined.

The relations described remain true as the curve is traced, and the motion of the stylus is continuously resolved into the two rectangular components: one in the direction of the amplitude, producing rolling of the spheres, and the other in the direction of the length of the curve, revolving the integrating cylinders around the several spheres. The integrating cylinders are rolled in such a manner as to add, algebraically, the properly resolved components of the amplitude increments; or, in other words, they perform the process of true, continuous integration as required for the evaluation of the Henrici integrals. The operations of selective analysis and summation are secured by the beautifully related mechanical movements, which proceed so smoothly that they seem almost mysterious. Because of the design and workmanship, which produce continuous movements with the complete elimination of lost motion, remarkable precision is attained, as is illustrated by numerical examples in the latter part of this paper.

The maker of the analyzer has so proportioned and adjusted the sizes of the various parts of the integrators that the readings on the dials are not only *proportional* to the coefficients of the various terms of the Fourier equation, but there are also automatically incorporated in the readings a proportionality factor, the factor π, and the algebraic signs, so that the readings are *exactly equal* to the *amplitudes expressed in millimetres,* without any reduction except for the factor n as mentioned below. The dials indicate 0.1 millimetre directly and 0.01 millimetre by estimation, and they have a capacity for 2000 millimetres before repeating.

The readings of the first set of dials are the amplitudes of the fundamental sine and cosine curves. In the fundamental wave-length there are, of course, two wave-lengths of the second component, and in tracing the curve the second integrator operates over the two waves of this order and at the end its dials show the sum of the amplitudes for the two waves, or twice the amplitude for this component; the third integrator has integrated three wave-lengths, etc. Therefore, at the conclusion of the tracing of the complex curve, any integrator for the nth term indicates n times the corresponding amplitude, which accounts mechanically for the presence of the factor n in the denominator of the Henrici integrals.

The maker has chosen 400 millimetres (about 15¾ inches) for the wave-length; this provides a frame for the instrument which accommodates five integrators, and when the stylus is moved across the wave it gives a movement to the wire which is suitable for putting the integrators into proper action. If the wave-length were less, the disks for the wire would have to be correspondingly smaller, resulting in increased difficulty of revolution of the integrating cylinders, as mentioned in the next section. However, the instrument may be adapted to any specified shorter wave-length by providing new disks for the wire adjusted to have effective circumferences which produce complete revolutions of the integrators in the order of the natural numbers.

When only certain particular components are required, a special set of disks may be provided to evaluate these. For instance, in electric alternating-current waves there are present only odd-numbered terms, and the disks may be arranged for one, three, five, seven, nine, etc., turns of the integrators.

In the development of the theory of the analyzer the general integration contains other parts than the ones so far considered; it is shown that when the integration is taken around a closed curve under conditions such as are involved in the practical operation of the analyzer, these other integrals are eliminated. It is interesting to note that these terms are also present in the mechanical integrations, and that they are automatically eliminated from the readings only at the conclusion of the tracing.

While one wave-length of a complex curve is being traced, the integrating cylinders of any sphere are rotated by larger or smaller amounts, depending upon the instantaneous amplitude. Finally, when the end of the exact wave-length has been reached and each cylinder has been revolved around its sphere an exact integral number of times, the rotation of the cylinder then registered is proportional to the true amplitude of the sine or cosine component whose wave-length is equal to the distance the stylus moved transversely during *one* complete revolution of the cylinder around the sphere; the effects of all other harmonic component curves will have been automatically eliminated from this particular integrator. Further, the sphere of an integrator arranged for evaluating a component of a certain order which in a particular curve has the value zero (as in one of the test curves described later) actually rolls just as much in the amplitude direction as

does any other sphere of the series; the integrating cylinders, revolving around their sphere *n* times, at several different times in the process of analysis show large readings which are zeroized only at the *end* of the tracing.

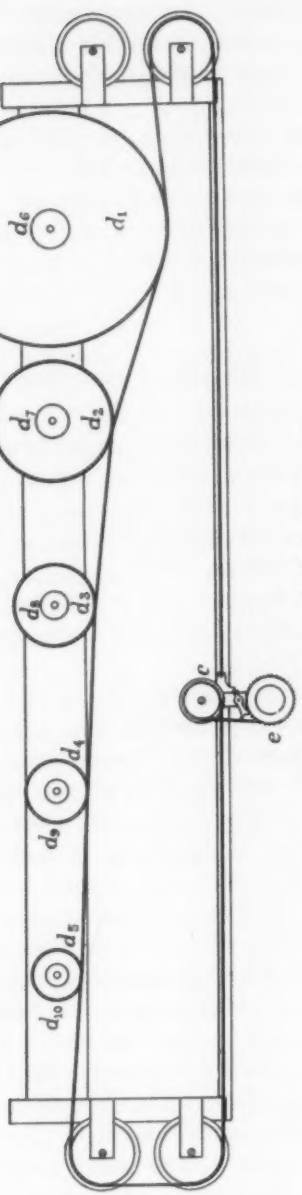
When there are *inharmonic* components in the curve, the method of analysis and the instrument here described are not directly applicable. If, however, such a curve is traced, the integrators will indicate the amplitudes of the respective terms of the infinite series of *harmonic* components which may be considered equivalent to the inharmonic components *in so far as the terms of the specified orders are involved.*

EXTENSION OF THE ANALYZER FOR THIRTY COMPONENTS.

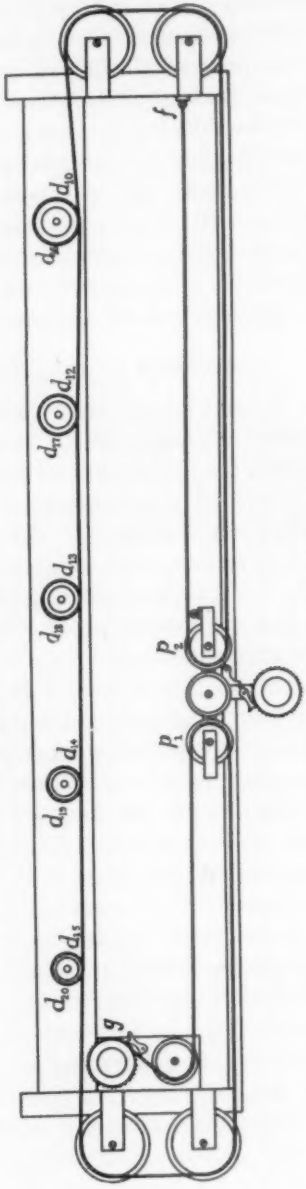
When arrangements were being made for the construction of an analyzer suitable for the investigation of sound waves, Mr. Coradi, the maker, upon being asked whether an instrument could be provided which would determine more than ten components, replied as follows: "The Henrici analyzer has never been arranged for more than ten elements. The diameters of the disks of the eleventh and following elements would become too small to be able to put the integrating apparatus in movement in a correct manner."

In accordance with this opinion, and because at that time it was thought that sound waves in general would not contain more than ten components, an instrument was purchased arranged for ten components. This analyzer was found sufficient and very satisfactory for the study of curves representing the sounds of the flute. When other sounds, as those of the clarinet and oboe, were investigated, it appeared that at least twenty components must be considered. This necessity led, in 1910, to an addition to the analyzer, extending its range to thirty components. Six years of use, during which thousands of analyses have been made, has shown that the arrangement is very practicable. The new device provides simply for doubling the motion of the wire caused by the travel of the tracing stylus, which provision makes possible the use of larger disks for revolving the integrators, thus obviating the difficulty mentioned by Mr. Coradi.

The scheme of the original wire arrangement is shown in Fig. 5. The wire is attached to the tracing carriage at *c*, and is threaded around the guide pulleys and around the integrator



Original scheme for wire for ten components.

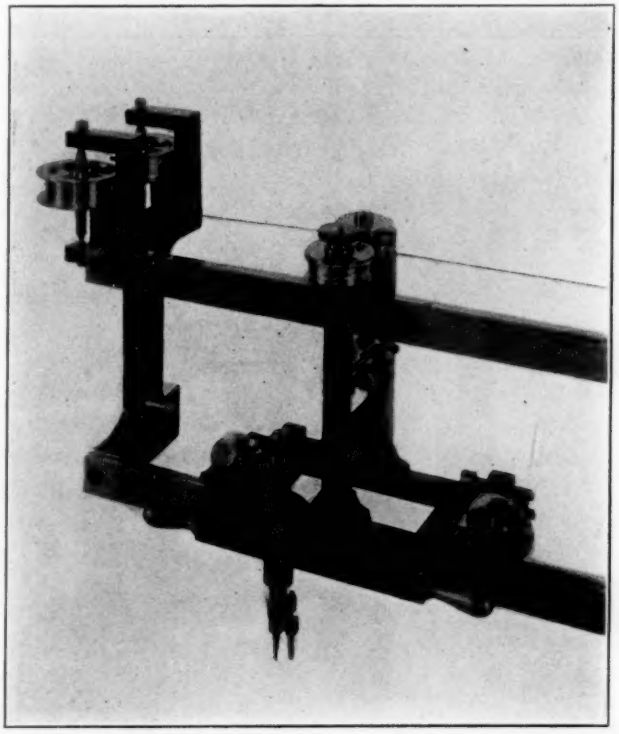


New scheme for wire for thirty components.

FIGS. 5 AND 6.

disks, as shown, and is brought back to the carriage, where it is held taut by winding on the supply drum e, which is held in place by a pawl and ratchet. The effective circumference of the disk d_1 for the first component is 400 millimetres, the wave-length, while the effective circumference of the disk for the tenth component is 40 millimetres, giving a diameter of less than 13 milli-

FIG. 7.



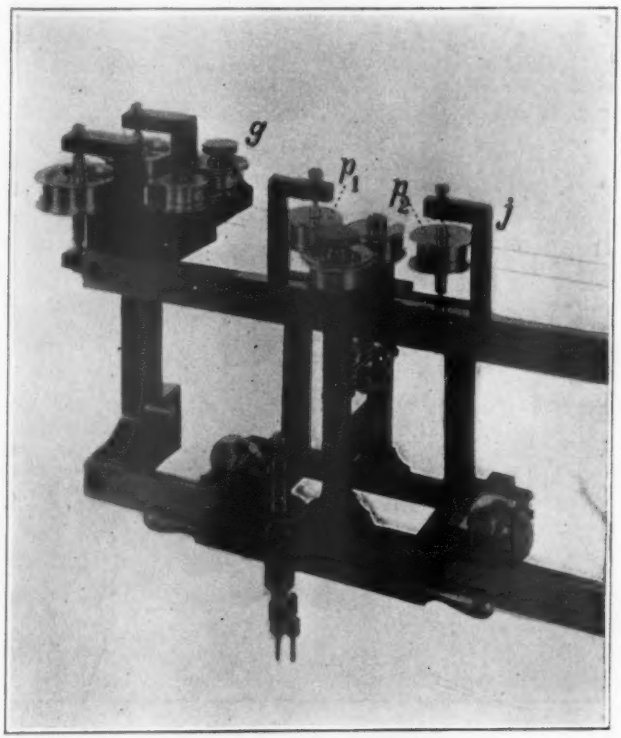
Tracing carriage in original form.

metres. The analyzer is always used in its original form for evaluating the first ten components.

When components of higher order are to be evaluated, a new set of five double-disks is attached to the several integrators, and the wire is arranged according to the new scheme shown in Fig. 6. The wire is attached to the frame at f, and is threaded around a free pulley p_2 on the carriage, around the end pulleys and disks as

shown, and around a second free pulley p_1 on the carriage to the new winding drum at g. Any travel of the carriage now causes a movement of the wire of double the amount. For the eleventh component the effective circumference of the disk d_{11} is $2 \times 400 \div 11 = 72.7$ millimetres, and for the twentieth component it is $2 \times 400 \div 20 = 40$ millimetres, the same as for the tenth component in the original wire scheme.

FIG. 8.



Tracing carriage with new attachments.

A third set of five double-disks has been provided for the components from 21 to 30, the effective circumference of the latter being $2 \times 400 \div 30 = 26.6$ millimetres. When the wire is prepared as described in the next section, the determination of thirty components is entirely practicable. However, since the wire stretches under the increased pull required to revolve the integrators of

higher orders, the last five components are usually determined by two tracings in groups of three and two, respectively, instead of in one group of five.

The nature of the additions to the analyzer to adapt it to the determination of the components of higher orders is shown by a comparison of Figs. 7 and 8: Fig. 7 is a view of the tracing carriage and one end of the frame in the original form, and Fig. 8 is a view of the same parts with the additions. The new parts consist of the rectangular frame *j*, Fig. 8, rigidly attached to the tracing carriage, and the two free pulleys, p_1 and p_2, and of the duplicate guide pulley and winding drum with their support attached to the end of the frame at *g*. There are two new hooks attached to the opposite end of the frame in the position indicated by *f*, Fig. 6. There are also the two new sets of five each of double-disks for the integrators, which are shown on the rack at the back of the view given in Fig. 1.

PREPARATION OF WIRE FOR THE ANALYZER.

The transverse movement of the stylus of the analyzer during the process of tracing a curve is transmitted to the integrators by means of a wire. The wire provided by the maker of the instrument was of copper, silver plated, having a diameter of about 0.27 millimetre (about No. 29 of the Brown & Sharpe wire gauge) and a breaking strength of about 4.5 pounds. Such wire serves fairly well when determining the first ten components, though it is rather soft and subject to stretching, which causes the phases of the revolving integrators to lag slightly. The pull on the wire increases in proportion to the number of revolutions of the disks, and this, added to the rolling action on the wire as it turns the disks, causes so much stretching that the copper wire is not suitable for components above ten.

Experiments have been made with wire of the following materials: Copper, iron, steel, nickel, hard brass, soft brass, German silver, platinoid, and manganin. The steel and hard-drawn brass wires, while free from stretching, were too stiff and springy: where the wire was wrapped around the disks the tendency was to open out and allow slipping. Most of the other wires proved to be too soft and likely to stretch. Soft German silver seemed to be the only suitable material.

The preparation of the wire is as follows: The stock is soft

German silver wire of No. 28 Brown & Sharpe gauge, as obtained from the usual supply dealers, which has a diameter of about 0.31 millimetre. One end of a piece of the wire about 70 inches long is fastened in a vise and the other end is wrapped around the hook of a spring balance. The wire is subjected to a slowly-increasing pull up to about 8 pounds, which is continued for two minutes. This causes a stretch of about 4 inches, after which the wire seems to acquire a permanent set and it may be subjected to an additional pull of one or two pounds without further permanent elongation. This stretching is a kind of tempering process. The wire is next drawn through a steel draw-plate, reducing the diameter to about 0.29 millimetre, and increasing the length to about 84 inches. Finally the wire is drawn through a second and very accurate draw-plate which reduces the diameter to 0.28 millimetre, the length now being about 90 inches; it has a mild spring temper and a breaking strength of about 13 pounds. The wire thus prepared may be used on the analyzer for more than a hundred analyses before it breaks; for the higher-element integrations there is a slight stretch, perhaps amounting to one millimetre, which must be taken up by the winding drum after each such tracing.

A chain, such as the fusee chain of watches, would, no doubt, be very suitable in place of the wire; such chain is used with entire satisfaction in the 32-element harmonic synthesizer described by the author in this JOURNAL for January, 1916. For use with the analyzer a small-sized chain about eight feet long would be required; it is necessary to unthread the chain frequently, and there would be great danger of its becoming kinked and broken. Wire is much more convenient and has been found satisfactory.

THE ANALYZING BOARD.

The analyzer in operation rolls back and forth in the direction of the amplitude of the curve, and it may be placed on any flat surface, as a table, and roll over the paper on which the curve is drawn. To secure a uniform and rectilinear rolling, and to facilitate the operation in general, a special board has been arranged, having for its foundation a drawing-board 30 by 42 inches in size. Two strips of hard wood about one inch wide and one-fourth inch thick are set into the board about an eighth inch, so that the upper surfaces of the strips are about an eighth inch above the surface

of the board; these strips are about 21 inches apart, forming tracks on which the rollers r_1 and r_2, Fig. 1, may run.

A third strip of hard wood is placed against the right edge of the right track, forming a guide for the roller r_2. Two stops are provided near the front edge of the board, against which the analyzer is rolled, setting the instrument as a whole with its axis perpendicular to the tracks. A ledge is placed on the front of the board to prevent the analyzer from accidentally rolling off, and a glass house for the analyzer and attachments is permanently arranged as shown in Fig. 1.

ENLARGING THE CURVES FOR ANALYSIS.

Curves which are to be analyzed with the Henrici analyzer must be drawn to a standard wave-length of exactly 400 millimetres, as has been explained. If a wave is drawn exactly to the wave-length of 200 millimetres, then the integrators for the components 2, 4, 6, etc., of the 400-millimetre series will, of course, give the components 1, 2, 3, etc., for the wave 200 millimetres long, and similarly for other aliquot parts of 400 millimetres.

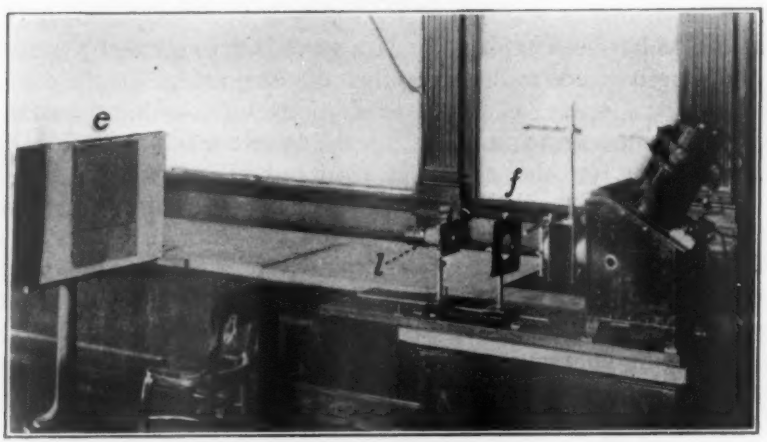
The curves provided by observation are rarely, if ever, of the exact wave-length required, and they must be redrawn. This may be done by plotting numerical data to the proper scale, or the curve may be enlarged with the help of proportional dividers, a pantograph, or other draughting instrument. A photographic camera or enlarging apparatus may be useful. When the original curve has been photographically recorded on a plate or film, a projecting lantern may be the most convenient enlarging arrangement.

The photographs of sound waves obtained with the phonodeik [3] are commonly made on films five inches wide and the wave-lengths vary from 25 millimetres to 100 millimetres. These curves are enlarged with the apparatus shown in Fig. 9, consisting of an optical bench projection apparatus having a lens l of large size, with the addition of a special film holder f and an easel e.

The film holder f consists of a frame with an opening covered by a glass plate; this frame is adjustable in two rectangular directions by means of micrometer screws, and is capable of rotation about an axis perpendicular to its own plane. A smaller frame with a glass plate is hinged to the larger one. The film is placed between the two glass plates, and the image of the curve is projected on the easel. The frame is adjusted till the image is in a suitable position for the tracing.

The easel consists of a drawing-board so mounted on a stand that the optical axis of the projection apparatus is perpendicular to the board at its centre. The easel rolls on ball-bearing castors and has a guide resting against a track (the edge of the long table, as shown in the illustration), which permits the easel to be moved forward and backward, the board remaining at all times in the proper relation to the projecting lantern. On the easel are ruled vertical lines 400 millimetres apart and also horizontal lines. The distance of the easel from the film and the position of the lens are adjusted till the image of one wave-length of the curve is exactly 400 millimetres long and is in focus. The wave-length is best

FIG. 9.



Lantern and easel for enlarging curves.

determined by the points where two consecutive waves cross the axis (or any base line) in the same phase; if no base line is given, the sharp crests or troughs, or other definite points of two consecutive waves which are in the same phase, may be used. A piece of paper, 19 by 24 inches in size, is placed on the easel and the wave is traced with a pencil, one wave-length only being required; the axis or base line is drawn, and the curve thus obtained is ready for analysis.

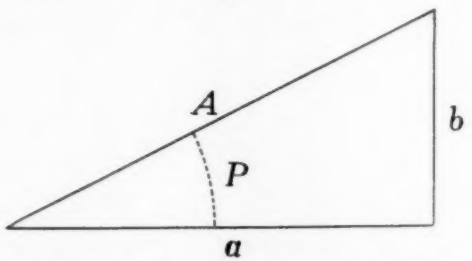
The drawing of all curves to this large scale, on a standard size of paper, facilitates comparison and filing. The harmonic synthesizer [4] used in this work draws curves of the same size, and a

direct comparison of the original and the synthesized curves can always be made. When the operation of enlarging is performed in routine manner, the time required is less than five minutes for each curve.

MACHINE FOR CALCULATING AMPLITUDES AND PHASES.

The equation of a curve as given by harmonic analysis is in the form of a double series of sines and cosines, as explained in the first part of this paper. Another form of the equation, consisting of a series of sines only (or of cosines only), with epochs or phases for the several terms, is more suitable for expressing the results of a physical investigation. The latter form presumably corresponds to the physical phenomena represented, while the former is a mathematical expression resulting from the Fourier method of derivation. It is therefore necessary to reduce the data given by the analyzer to determine the amplitudes and phases of the components of a curve, and this is carried out in accordance with the following principle.[2]

FIG. 10.



Amplitude and phase relations of component and resultant harmonic motions.

The Fourier equation, form III, having on one side a constant term and a series of pairs of sine and cosine terms, may be reduced to the following equivalent form:

$$y = A_0 + A_1 \sin(\theta + P_1) + A_2 \sin(2\theta + P_2) + A_3 \sin(3\theta + P_3) + \ldots. \qquad \text{IV}$$

if $a_0 = A_0$ and if each pair of terms, n being the order of the term, is reduced as follows:

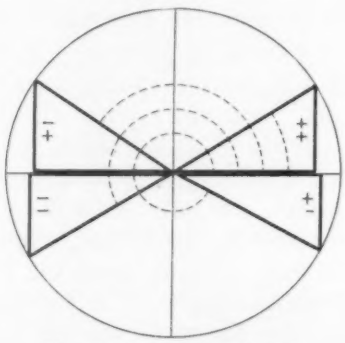
$$a_n \sin n\theta + b_n \cos n\theta = A_n \sin(n\theta + P_n).$$

The relations expressed in this equation are shown by trigonometry to be true when

$$A_n = \sqrt{a^2_n + b^2_n}, \text{ and } P_n = \tan^{-1}\frac{b_n}{a_n},$$

and these conditions are involved in the relations of the parts of a right triangle. If the base of a triangle is made equal to a and its altitude equal to b, Fig. 10, then the length of the hypothenuse is

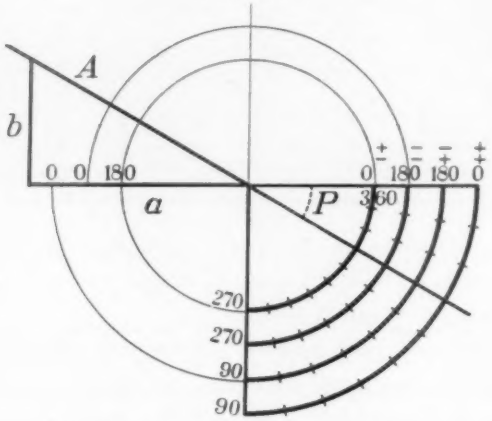
FIG. 11.



Phase angles in four quadrants.

equal to A, as expressed above, and the angle which the hypothenuse makes with the base is equal to P. It is necessary, therefore, to reduce each pair of coefficients given by the analyzer to deter-

FIG. 12.



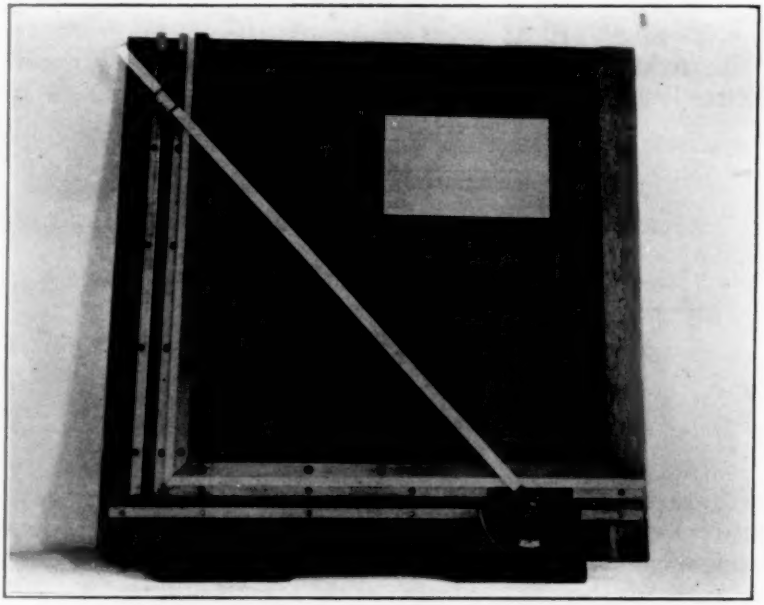
Scheme for measuring phases in one quadrant.

mine A_n and P_n as given by the last two equations. According to the values of n, these equations give the quantity A_1 the amplitude of the first component or fundamental, P_1 its phase, A_2 the amplitude of the second component (octave), P_2 its phase, and so

on. An equivalent expression for the analysis involving cosines only, with phases, can be obtained in a similar manner.

The values of the amplitudes and phases may be obtained by numerical calculation as described in the next section, but it has been found possible to facilitate greatly the reduction by using a machine which has been devised and constructed in our own laboratory. This amplitude-and-phase calculator is essentially a machine for solving right triangles, with the addition of a special angle measurer.

FIG. 13.



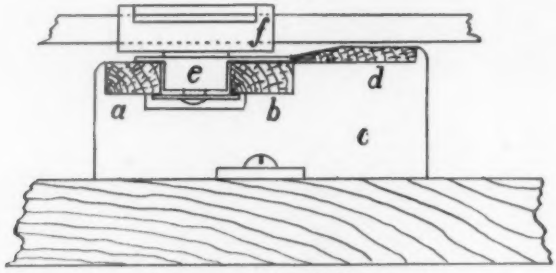
Machine for calculating amplitudes and phases in harmonic analysis.

The analyzer gives directly the numerical values of the coefficients, na_n and nb_n, of the several terms of the general Fourier equation, and each coefficient may have either the positive or the negative sign. For given numerical values of the coefficients there is but one value of the resultant amplitude, $A = \sqrt{a^2 + b^2}$, but the phase $P = \tan^{-1} \frac{b}{a}$ may have any one of four different values, according to the combination of signs, as shown in Fig. 11: For $+a$, $+b$, the angle will have a value between 0° and 90°; for $-a$, $+b$,

its value is between 90° and 180°; for $-a, -b$, it lies between 180° and 270°; and for $+a, -b$, it is between 270° and 360°. A machine was constructed on the plan of this diagram which measured around a circle; later this was reduced to a quadrant machine with a special angle measurer having four graduations of a quadrant each numbered to correspond to the four possible combinations of algebraic signs, as shown in Fig. 12. Since a single graduated arc may be provided with two sets of numbers, one on each side, two graduations are sufficient, and the machine now in use is so constructed.

The amplitude-and-phase calculator, Fig. 13, the base of which is a drawing-board 24 inches square, consists of two grooves at right angles to each other, provided with linear scales 50 centimetres long, graduated to single millimetres; in the grooves are

FIG. 14.



Cross-section of vertical groove.

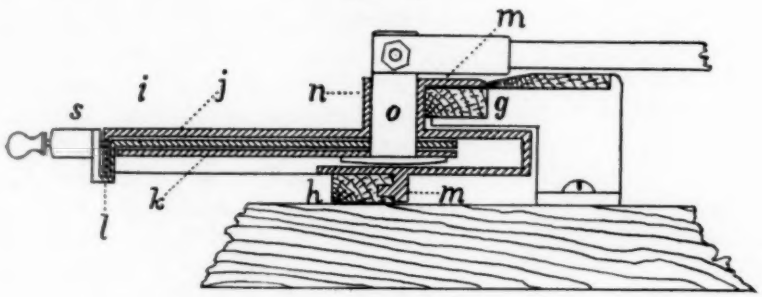
slides carrying the graduated hypothenuse bar, which is 73 centimetres long. One end of the bar is attached to the angle measurer, while the other end slides through a support to which is attached an index for showing the length of the hypothenuse.

The vertical groove, which is about half an inch wide, is made by fastening two strips of hard wood, *a* and *b*, Fig. 14, to brass supports *c;* the bevel-edged graduated scale is shown at *d*, and the slider at *e*. A spring on the under side of the slider gives a smooth and firm movement. The hypothenuse bar slides through the cloth-lined casing *f*, which is pivoted over the centre of the groove.

The zero end of the hypothenuse bar is pivoted over the horizontal groove and is attached to the axis of the graduated quadrant, so that the quadrant is turned through the angle which gives

the phase as indicated by the stationary index lines described below. The two guides, *g* and *h*, Fig. 15, which form the horizontal

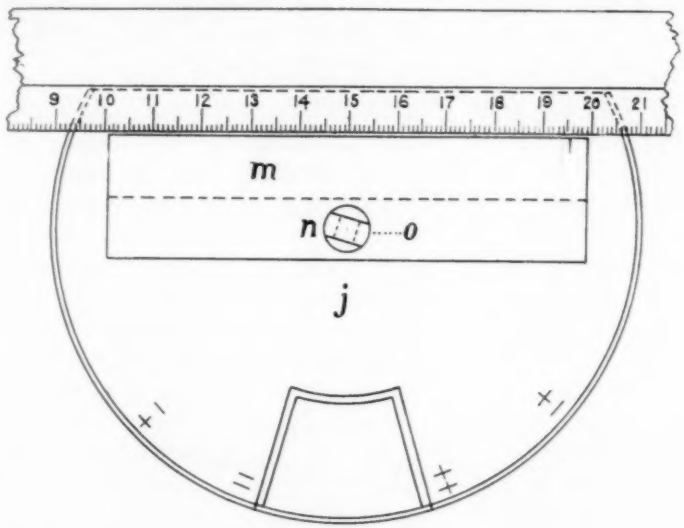
FIG. 15.



Cross-section of angle measurer.

groove, are at different levels to allow the angle measurer *i* to pass over the lower guide.

FIG. 16.

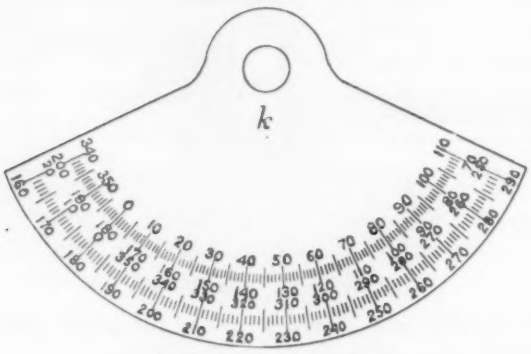


Top plan of angle measurer.

The novel feature of the instrument is the angle measurer, which consists of three parts, the outer casing *j*, Fig. 15, the graduated quadrant *k*, and the index cover *l*. The outer casing *j*, Figs. 15 and 16, carries on its upper and lower faces the guides *m*

which cause it to slide accurately in the groove. This casing also provides a bearing *n* through which passes the stud *o* of the graduated quadrant, so that the centre of the graduation is always

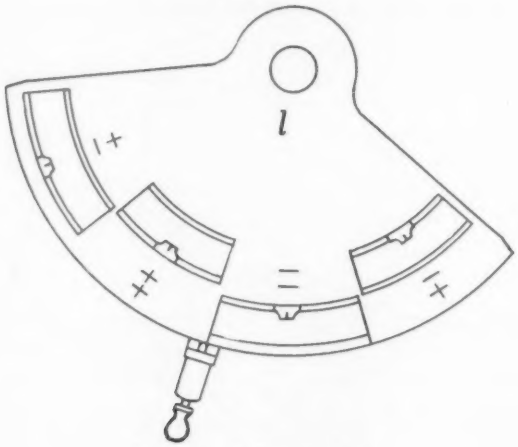
FIG. 17.



The graduated quadrant.

on the centre line of the groove. To the upper end of the stud is attached the zero end of the hypothenuse bar, the nominal zero being over the centre of the horizontal groove.

FIG. 18.



Index-cover for the quadrant.

The graduation of the quadrant, shown in Fig. 17, is in accordance with the scheme of Fig. 12; the graduation is extended a few degrees beyond the quadrant on each side to facilitate reading.

The adjustable index cover, Fig. 18, has four narrow apertures, which, when combined with the aperture in the outer casing as shown in Fig. 16, allow one graduated arc and any one, and only one, of the four sets of numbers to be seen at one time, according to the position of the cover. A spring stop *s*, Figs. 15 and 18, is attached to the cover; there are four positions for this catch, marked for the four possible combinations of the algebraic signs of the coefficients *a and b*: $\dot{+}$, $\pm$, $\mp$, and =; when the cover is set, one reads the true phase angle without any reduction.

The graduations for the horizontal and vertical scales begin about 1½ inches from the junction of the grooves, thus bringing the indexes to convenient locations on the sliders. There are several geometrical methods of locating and verifying the several indexes for the linear and circular graduations; when the angle measurer is placed under the vertical groove and is so adjusted that the vertical slider can be moved from one end to the other of its groove with *no change* in the angle of the hypothenuse bar, then the horizontal slider must be in its zero position, and the index must indicate zero on the horizontal scale; the indexes for the hypothenuse bar and for the vertical slider must both show the *same* readings throughout the motion of the slider; the indexes on the cover of the quadrant must show 90° for the $\dot{+}$ and for the $\pm$ positions, and 270° for the = and for the $\mp$ positions. Other similar tests must be made, which will be evident when required.

The linear scales are 50 centimetres long; often the values of *a* and *b* given by the analysis are less than 50 millimetres, in which cases the reduction is carried out by using a centimetre on the machine for a millimetre of the analysis; by reading to single millimetres the result is obtained to tenths of a millimetre. If the values of *a* and *b* are between 50 millimetres and 100 millimetres, it is a simple procedure to use a half of the values for the settings, and to double the hypothenuse reading for the result. If the values of *a* and *b* are still larger, their actual values in millimetres are set off on the machine and the readings are made to tenths of a millimetre. The phases may be read to a tenth of a degree, though usually it is sufficient to read to the nearest half degree.

It is often desirable to state the relative phases of the various components when the phase of the first component is 0°. These

relative phases are obtained by subtracting from the phase of each component n times the value of the phase of the first component (n being the order of the component). A special machine has been devised for transforming the calculated phases into the relative phases when $P_1 = 0°$, but the machine has never been constructed, since the harmonic synthesizer previously referred to gives the relative phases without extra work.[4] In the operation of verifying the analysis of a curve by synthesis, the amplitudes and phases of each component are set up on the synthesizer; it is then only necessary to turn the handle of the synthesizer until the phase dial of the first component indicates 0°, when the direct readings of the phase dials of the other components are the relative phases desired.

CARDS AND CHARTS FOR RECORDS OF ANALYSES.

The comparison and filing of the results of the analyses of many curves is facilitated by using a card form for the record; five such forms have been tried, two of which will be described. Each card, 5 by 8 inches in size, contains the data for ten components; white cards are used for the components from 1 to 10, buff cards for components 11 to 20, and salmon-colored cards for components 21 to 30; blue cards are provided for averages, special data, etc.

When the reduction is to be made by numerical calculation, the form of card shown in Fig. 19 is convenient. The readings of the dials of the analyzer are recorded in the horizontal lines na_n and nb_n; the squares of these numbers are taken from printed tables, such as Crelle's "Rechentafeln," or Barlow's Tables;[6] the sums of the two square numbers for the several components are placed in the line $[nA_n]^2$, and the square roots of these sums, taken from the printed tables, are placed on the next lower line; the latter numbers divided by the respective values of n are the true amplitudes of the harmonic components and are recorded in the line labelled *Amplitude*. The logarithms of the numbers nb_n and na_n are placed in the appropriate lines, and the differences of the logarithms corresponding to each component are the logarithmic tangents of the phase angles, log tan p, and the corresponding angles (taken in the proper quadrants according to the algebraic signs as shown in Fig. 11) are the true phases of the components.

When the calculation of amplitudes and phases is to be made

by machine, as described in the preceding article, the form of card shown in Fig. 20 is more convenient. The readings from the

FIG. 19.

CASE SCHOOL OF APPLIED SCIENCE — DEPARTMENT OF PHYSICS

ANALYSIS OF SOUND-WAVES.

No. 1690 Source Organ Pipe - "Reedless Oboe." Date April 23, 1915

1-10 Tone C_3 Abs. N 260 Purpose Analysis.

component, n	1	2	3	4	5	6	7	8	9	10
na_n	+ 22 6	+ 93 6	+ 101.1	+ 76.1	+ 44.5	+ 49.1	+ 44.8	+ 24.9	- 11.5	- 7.1
nb_n	+ 94.1	- 87.2	- 42.5	- 7.5	- 26.1	- 10.6	- 3.8	- 66.7	- 36.9	- 21.7
$[na_n]^2$	510.76	9920.16	10221.21	5791.21	1980.25	2410.81	2007.04	620.01	132.25	50.41
$[nb_n]^2$	8851.81	7603.84	1806.25	56.25	681.21	112.36	14.44	4448.89	1361.61	470.89
$[nA_n]^2$	9365.57	17524.00	12027.46	5847.46	2661.46	2523.17	2021.48	5068.90	1493.86	521.30
nA_n	96.8	132.4	109.7	76.5	51.6	50.2	45.0	71.2	38.7	22.8
log nb_n	1.9736	1.9405	1.6284	0.8751	1.4166	1.0253	0.5798	1.8241	1.5670	1.3365
log na_n	1.3541	1.9583	2.0048	1.8814	1.6484	1.6911	1.6513	1.3962	1.0607	0.8513
log tan p	0.6195	9.9122	9.6236	8.9937	9.7682	9.3342	8.9285	0.4279	0.5063	0.4842
p	76.°	319.°	337.°	354.°	330.°	348.°	355.°	290.°	252.°	252.°
Amplitude	96.8	66.2	36.6	19.1	10.3	8.4	6.4	8.9	4.3	2.3
Phase										
Intensity										

Remarks — Sum — Analyzed R.F.H. — Synthesized

Card for record of analysis, for numerical reduction.

FIG. 20.

CASE SCHOOL OF APPLIED SCIENCE — DEPARTMENT OF PHYSICS

ANALYSIS OF SOUND-WAVES

No. 1690 Source Organ Pipe - "Reedless Oboe." Date April 23, 1915

1-10 Tone C_3 Abs. N 260 Purpose Analysis.

component, n	1	2	3	4	5	6	7	8	9	10
na_n	+ 226	+ 996	+ 101.1	+ 761	+ 44.5	+ 49.1	+ 44.8	+ 249	- 11.5	- 7.1
nb_n	+ 94.1	- 87.2	- 42.5	- 7.5	- 26.1	- 10.6	- 3.8	- 66.7	- 36.9	- 21.7
nA_n	96.8	132.3	109.4	76.3	51.6	50.2	45.0	71.1	38.7	22.8
k_n ( )										
nA_nk_n										
$[nA_nk_n]^2$										
A_n	96.8	66.2	36.5	19.1	10.3	8.4	6.4	8.9	4.3	2.3
P.	76.°	319.°	337.°	354.°	330.°	347.°	355.°	290.°	252.°	252.°
A_nk_n										
Amplitude, %										
Phase										
Intensity, %										

Remarks — Sum — Analyzed R.F.H. — Synthesized

Card for record of analysis, for reduction by machine.

analyzer are recorded as before in the lines labelled na_n and nb_n. The numbers for each component are set off on the amplitude-

and-phase calculator, and the readings of the hypothenuse bar are recorded on the line nA_n, and the phases (the index cover being set to correspond to the signs of a and b in each case) are read directly and recorded on the line P_n. The values of nA_n being divided by the respective values of n give the true amplitudes which are recorded on the line A_n. This completes the analysis. The other data for which provision is made on the card illustrated do not belong to the process of harmonic analysis, but are connected with the correction and reduction of the analyses of sound waves by a particular method which is fully described elsewhere.[3]

The scheme to be adopted for the graphic presentation of the results of a harmonic analysis will depend upon the nature of the phenomena represented. In the investigation of sound waves, the results may be given in terms of the intensity or loudness of the separate components, instead of the amplitude, and the relative values may be shown by plotting on a logarithmic scale of frequencies corresponding to the tones of the musical scale. A description of special charts and plotting scales suitable for such representations has been given in the explanation of the analysis of sound waves just referred to.

PRECISION ATTAINED IN HARMONIC ANALYSIS.

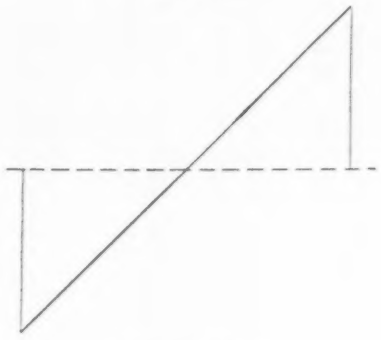
Harmonic analysis is usually applied to curves obtained by plotting observed numbers as coördinates or by graphically recording vibrations with the aid of some form of oscillograph. The forms of such curves can hardly be those of the resultants of a few simple harmonic components. Though the phenomenon represented by a curve is made up of a finite number of periodic components, yet the curve itself may be slightly distorted and will require an infinite series of components, many being of very small magnitude, for its exact reproduction. The methods of analysis by numerical reduction of the measures of the coördinates of a curve have the precision of ordinary graphical methods of investigation; however, many of these methods become much less precise, the higher the order of the component being evaluated.[7, 8]

The Henrici harmonic analyzer probably gives the values of the components with greater precision than it is practicable to obtain by any other method. Numerous tests have been made to determine its precision, and the results of several trials will be explained. Each curve was drawn to the standard size of one

wave-length equal to 400 millimetres, and each was analyzed to thirty components. The numerical results given in the tables are the actual amplitudes in millimetres of the several indicated components, as given by the mechanical analyzer. For Table I the readings were taken to hundredths of a millimetre, while for Table II they were taken only to tenths of a millimetre, a degree of refinement quite sufficient for the tracing of curves drawn on paper. The phases of the components, which are obtained from the readings, are not given at this time, since they are determined with the same order of precision as are the amplitudes.

Table I gives several analyses of each of two test curves. The

FIG. 21.



A test curve, $y = x$.

analyses of the first set are for a straight line inclined at an angle of 45°, $y = x$, Fig. 21, which has an infinite series of components, represented by the Fourier equation (the wave-length being 400),

$$y = \frac{400}{\pi}(\sin x - \tfrac{1}{2}\sin 2x + \tfrac{1}{3}\sin 3x - \dots).$$

The computed values of the components are given in the column headed *calc;* the columns M – 1 and M – 2 give the values of the components obtained from two analyses made by D. C. M., the tracing being done with great care; the column S – 1 gives the values obtained by D. H. S., when the tracing was done in the usual manner of routine analysis. The average departure of the means of the two analyses by D. C. M. from the true values is 0.022 millimetre, which is one twenty-thousandth of the wave-length, or one ten-thousandth of the amplitude of the original

curve, or one six-thousandth of the amplitude of the fundamental component. The maximum departure in the single analysis by D. H. S. is 0.25 millimetre in the value of the nineteenth component.

TABLE I

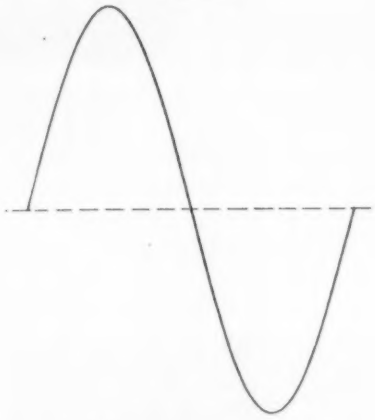
Analyses of Special Test Curves.

Comp.	Amplitudes of components in millimetres						
	Straight line, $y = x$				Sine curve, $y = \sin x$		
n	Calc.	M – 1	M – 2	S – 1	H – 1	H – 2	H – 3
1	127.32	127.30	127.30	126.90	250.03	250.27	250.03
2	63.66	63.55	63.60	63.35	0.97	0.94	0.71
3	42.44	42.47	42.50	42.37	0.69	0.56	0.72
4	31.83	31.85	31.82	31.75	0.27	0.28	0.28
5	25.46	25.50	25.46	25.46	0.19	0.22	0.22
6	21.22	21.17	21.17	21.24	0.31	0.29	0.20
7	18.19	18.16	18.14	18.14	0.20	0.12	0.10
8	15.91	15.94	15.97	15.90	0.08	0.11	0.05
9	14.15	14.12	14.15	14.14	0.20	0.03	0.11
10	12.73	12.75	12.70	12.73	0.05	0.11	0.04
11	11.57	11.60	11.56	11.65	0.18	0.10	0.13
12	10.61	10.64	10.67	10.50	0.18	0.10	0.09
13	9.79	9.81	9.80	9.73	0.04	0.08	0.04
14	9.09	9.09	9.17	9.00	0.12	0.14	0.09
15	8.49	8.50	8.49	8.45	0.14	0.07	0.11
16	7.96	7.91	7.97	8.02	0.12	0.05	0.05
17	7.49	7.51	7.40	7.44	0.13	0.04	0.08
18	7.07	7.10	7.02	6.93	0.04	0.04	0.03
19	6.70	6.71	6.70	6.95	0.19	0.02	0.11
20	6.37	6.43	6.41	6.21	0.06	0.09	0.10
21	6.06	6.04	6.06	6.09	0.15	0.06	0.10
22	5.79	5.81	5.78	5.81	0.06	0.14	0.12
23	5.54	5.53	5.46	5.48	0.10	0.06	0.09
24	5.30	5.23	5.23	5.36	0.09	0.08	0.18
25	5.09	5.10	5.07	5.17	0.11	0.08	0.04
26	4.90	4.91	4.90	4.99	0.03	0.03	0.10
27	4.72	4.78	4.73	4.70	0.07	0.07	0.13
28	4.55	4.61	4.52	4.40	0.03	0.01	0.11
29	4.39	4.41	4.39	4.36	0.11	0.10	0.10
30	4.24	4.25	4.26	4.12	0.04	0.10	0.18

The analyses of the second set given in Table I are for a simple sine curve, Fig. 22, $y = \sin x$, three successive analyses, all made by R. F. H., being shown in the columns marked H – 1,

H – 2, and H – 3. This curve which was drawn by the harmonic synthesizer was presumed to have but one component, a fundamental of an amplitude of 250 millimetres. While all the higher components have very small values, components two and three have values which are not due to inaccuracies in reading. It is probable that these small readings correspond to real components existing in the curve; a very slight distortion might introduce an infinite series of very small components. The reality of the components is indicated by the fact that the successive analyses give values differing but little from each other. The average of all the readings of the three analyses for all components above the sixth

FIG. 22.



A test curve, $y = \sin x$.

is 0.09 millimetre, while the largest single value is 0.2 millimetre. The latter quantity is less than the width of the line which represents the curve. As already mentioned, the rolling spheres of the integrators for these higher components actually roll just as much in the amplitude direction as does the sphere for the first component, which has an amplitude of 250 millimetres; and the integrating cylinders, revolving around their spheres, at several different times in the process of analyzing the curve show large readings, which readings for a zero component are zeroized only at the end of the tracing; therefore it is not surprising that the final readings differ from zero by one- or two-tenths of a millimetre.

Table II gives three values of the analyses of each of two curves of unknown composition, the photographed curves of the sound waves from a clarinet, Fig. 23, and from an oboe, Fig. 24.

TABLE II

Analyses of Sound Waves

Comp.	Amplitudes of components in millimetres					
	Clarinet curve No. 85			Oboe curve No. 81		
n	M−1	M−2	S−1	M−1	M−2	S−1
1	30.3	30.3	30.7	90.5	90.5	90.9
2	7.2	7.2	6.9	77.5	77.1	76.8
3	20.8	20.6	20.8	37.8	37.8	37.4
4	2.2	2.2	2.0	31.2	31.2	31.9
5	1.1	1.3	1.5	42.6	43.1	42.7
6	5.8	5.8	6.0	12.9	12.4	12.6
7	7.1	7.2	6.6	46.3	46.9	46.6
8	6.9	7.2	7.3	34.6	34.5	34.5
9	17.0	16.8	17.2	14.9	15.5	15.2
10	11.8	11.6	11.9	6.2	5.9	6.1
11	23.8	24.1	23.2	0.7	0.7	0.7
12	34.9	35.3	35.2	3.3	3.7	3.5
13	20.0	20.3	20.8	5.0	5.1	5.0
14	8.9	8.8	9.6	0.6	1.1	0.8
15	2.2	2.2	2.7	4.3	4.5	4.4
16	1.2	1.0	0.4	3.9	4.0	3.9
17	1.4	1.4	0.9	2.9	2.9	2.9
18	0.8	1.0	0.9	1.5	1.4	1.5
19	2.4	2.4	2.3	0.8	0.3	0.6
20	2.3	2.1	2.3	2.5	2.6	2.5
21	3.7	3.5	3.7	2.4	2.4	2.5
22	3.5	3.2	4.1	0.4	0.4	0.4
23	3.1	2.8	2.0	1.7	1.5	1.6
24	7.3	7.0	6.3	1.6	1.1	1.3
25	5.3	5.4	4.5	0.8	0.5	0.7
26	2.8	2.5	2.7	0.3	0.3	0.3
27	0.7	0.8	0.9	0.5	0.5	0.5
28	0.2	0.2	0.2	0.9	0.9	0.9
29	1.0	1.1	1.0	0.8	0.7	0.8
30	0.3	0.3	0.3	0.5	0.2	0.3

These analyses were all made with only the ordinary care of routine work. The variation is of the order of 0.2 millimetre, which is less than the width of the line of the curve.

The conclusion is that the Henrici harmonic analyzer possesses an inherent accuracy much greater than can be taken advantage of in graphic work. The results are always accurate to a fraction of the width of the line representing the curve, and this precision

FIG. 23.

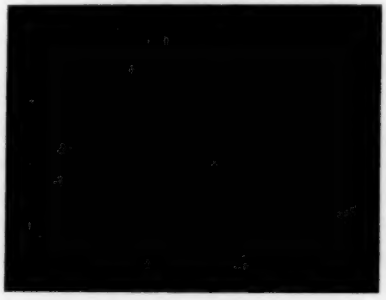
Photograph of the sound wave from a clarinet.

FIG. 24.

Photograph of the sound wave from an oboe.

is maintained uniformly for all the components, even to the thirtieth. If a curve could be traced exactly, the analyzer would undoubtedly give results of high precision, equalling one part in five thousand or more. Such accuracy is not approached by other

FIG. 25.



Photograph of the sound wave from an organ pipe.

instruments or methods of easy calculation with which the writer is acquainted.

Table III gives the results of three analyses, by different methods, of the same curve, the sound wave from an organ pipe,

Fig. 25: the first is purely mechanical (time required, thirteen minutes), the second is by the complete numerical reduction from thirty-six measured ordinates (time required, ten hours), and the third is the reduction from eighteen measured ordinates by means of a prepared schedule (time required for eight components, three hours).

TABLE III

Analyses of Organ-pipe Curve No. 1690 by Three Methods.

Amplitudes of components in millimetres			
Comp. n	Henrici analyzer	Steinmetz arithmetical	Grover schedule
1	96.8	97.0	96.6
2	66.2	66.0	66.5
3	36.5	36.7	37.2
4	19.1	19.0	19.9
5	10.3	10.4	13.6
6	8.4	8.9	9.7
7	6.4	7.2	8.4
8	8.9	9.0	12.0
9	4.3	4.1	
10	2.3	3.1	

TIME EFFICIENCY OF ANALYSIS BY MACHINE.

The analytical investigation of sound waves by the author has required the performance of hundreds of thousands of numerical operations, and an effort has been made to determine the most efficient methods of reduction. Some of the results of this study are as follows:

Addition.—The additions mostly required in the work referred to are of groups of ten (or twenty) numbers, each number having from one to four digits. A large number of such groups were added by two different computers, mentally and with each of three different machines. A typical result only will be given. R. F. H. added ten columns of ten numbers each mentally in 515 seconds, while the same additions with two machines required 834 seconds and 821 seconds respectively: L. W. S. required 510 seconds for the mental operations and 930 seconds for the machine additions. The fact that some of the machines recorded the numbers added is of no value in this work. The errors are few, and were no more and no less frequent in the mental operations than in the machine work.

Multiplication.—The multiplication of two numbers of from three to five digits each was performed with Crelle's "Rechentafeln" and with a Brunsviga calculating machine by R. F. H. With the tables 163 products were secured per hour, and with the machine 175 products per hour.

Division.—The only operation of division required in our work is the finding of the percentages of each of ten or twenty components, the sum of the components being given. This is carried out with a 20-inch slide rule, requiring three minutes to determine the percentages of twenty components.

Squares.—The squares of numbers of three digits are most easily taken from Crelle's "Rechentafeln," which, on two opposite pages, gives the squares of all numbers of from one to three figures.

Enlarging Curves.—The redrawing of a photographed curve to the standard size required for analysis, having a wave-length of 400 millimetres, requires, on the average, 4.1 minutes with the apparatus described.

Amplitudes and Phases.—The reduction of the coefficients obtained with the Henrici analyzer to obtain the amplitudes and phases of the components of a curve, by the numerical method represented by the card form shown in Fig. 19, using Crelle's "Rechentafeln" for the squares and square-roots, and four-place logarithm tables for the phases, requires twenty-eight minutes for ten components. The same reduction is made with the machine shown in Fig. 12, according to the card form of Fig. 20, in five minutes.

Synthesis.—The synthesis of a curve of ten components, forming a complete verification of the analysis, can be performed by the machine previously described, for ten components, in five minutes; for thirty components, in twelve minutes.

Analysis.—With the Henrici analyzer one tracing of a curve gives the data for five components; the time required for tracing a curve twice, including the changing of the wire, and for reading and recording the results, for ten components is ten minutes. Since an analysis is considered complete only when the data have been reduced to give the amplitudes and phases, the time for an analysis is then about fifteen minutes. As described in "The Science of Musical Sounds," pp. 122 and 136, the analysis and reduction of a certain curve by machine required thirteen minutes;

the analysis of the same curve by a method described by Steinmetz [2] required ten hours for ten components; the analysis with the help of prepared tabular forms as described by Grover [8] required three hours for the determination of eight components, the largest number for which a form was available.

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THE USE OF POWDERED COAL IN METALLURGICAL PROCESSES: A DISCUSSION OF THE ENGINEERING PRINCIPLES INVOLVED.*

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THE process of burning powdered coal is the best method by which to obtain perfect chemical combination of the air and coal, and by which the highest degree of perfection in combustion may be obtained if properly applied. There is no other fuel so responsive to correct application. The greatest precision is required in its control, and it may be said that, so far as the art of burning powdered coal has been developed, it is perhaps in too great a measure dependent upon the human equation.

The essential features necessary for success in the use of this fuel for metallurgical furnaces are:

First.—That the coal should have a high volatile content—low in ash.

Second.—That, after pulverizing, the moisture in the fuel should not exceed three-fourths of one per cent.

Third.—That it be pulverized so that at least 95 per cent. will pass through a 100-mesh sieve and over 83 per cent. through a 200-mesh sieve.

Fourth.—That the delivery of the coal to the furnace be uniformly controlled, regardless of the quantity required.

Fifth.—That it be delivered to the furnace in a thoroughly atomized state, and that combustion be completed while the coal is in suspension.

Sixth.—That in the application of this fuel the personal equation be eliminated as far as possible.

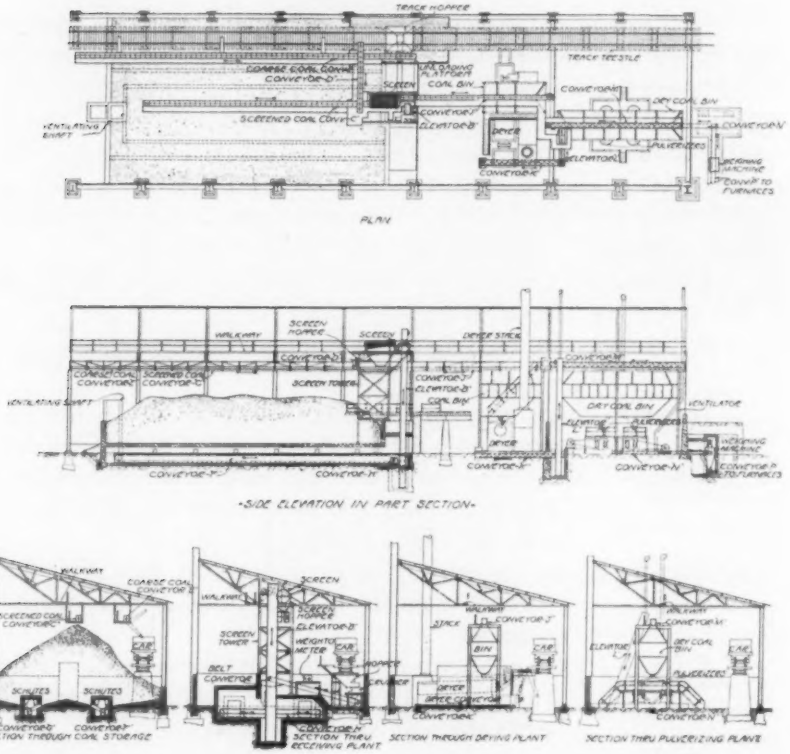
The use of powdered coal as a fuel necessitates the installation of an efficient crushing, drying, pulverizing, conveying, and distributing equipment and, in addition, ample storage room for coarse coal.

* Presented at a meeting of Mining and Metallurgical Section held Thursday, April 6, 1916.

Fig. 1 shows a plan, side elevation in part section, and four cross-sections of a coarse coal storage, drying, pulverizing, and conveying equipment.

The incoming coal is brought up an inclined plane to the elevated trestle and discharged from cars of the bottom-dump type into the track hopper. A pusher feed located on the bottom

FIG. 1.



of the track hopper controls the flow of coal to the crusher, the crushed coal falling by gravity on to belt conveyor "A," which discharges into the shoe of elevator "B." Belt conveyor "A" is fitted with a Merrick weightometer, which affords an accurate check on the tonnage received. The nature of the coal received determines the operation of the crushing rolls. In the case of slack coal, the crusher rolls are set apart and the coal falls

by gravity from the pusher feed through the crusher to the belt conveyor " A."

The discharge from elevator " B " is so arranged that it can either be spouted direct to conveyor " J," which feeds the coal storage bin over the dryer, or to the revolving screen. All coal placed in storage is spouted from elevator " B " to the revolving screen, which sizes it to cubes of 1 inch and under, the finer coal dropping into the hopper below the screen, thence on to flight conveyor " C," which distributes the coal in the storage. The coarser coal is discharged from the screen to the cross flight conveyor " D," thence on to the flight conveyor " E," from which point it is spouted to cars for use elsewhere.

Under the storage pile two concrete reclaiming tunnels are provided, each equipped with a flight conveyor. Chutes equipped with tunnel gates are spaced at proper intervals on each side of these tunnels, through which the coal from the storage pile travels by gravity on to the flight conveyor " F " or " G," and discharges into the reversible flight conveyor " H," which in turn discharges into elevator " B," from which point it is elevated and spouted to conveyor " J," distributing the fuel in the storage bin over the dryer.

A suitable feeding mechanism is located in the bottom of the coal storage bin over the dryer, which feeds the coal at a uniform rate into the upper end of a rotary dryer. The coal passes through the dryer, which removes the moisture, and is then discharged into the dust-proof screw conveyor " K," thence into the dust-proof elevator " L," thence to the dust-proof screw conveyor " M," which distributes the dried coal into the dust-proof storage bin over the pulverizers.

From the dust-proof dried-coal storage bin the coal travels by gravity to the feeding mechanism on the pulverizing mills. The powdered coal is discharged from the pulverizers into the dust-proof screw conveyor " N," from which point it is conveyed to the weighing machine, which automatically registers the weight of fuel pulverized. A by-pass connecting conveyors " N " and " P " provides a cut-out for the weighing machine and adjustments, and repairs can be made to this unit without shutting down the system. The weighing machine discharges into the dust-proof screw conveyor " P " connecting with the distributing system.

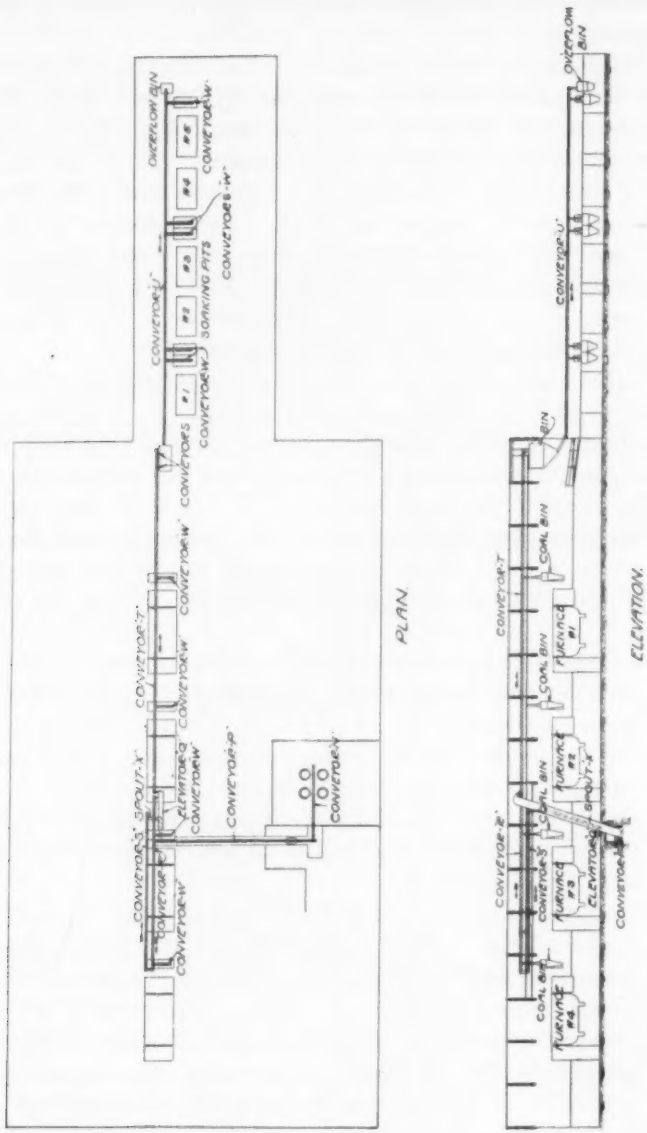


FIG. 2.

Fig. 2 shows a plan and elevation of a powdered-coal distributing system. This equipment furnishes powdered coal to four 50-ton open-hearth furnaces and five double soaking pits.

The dust-proof screw conveyor "P" carries the coal to the dust-proof elevator "Q," which discharges into the dust-proof screw conveyors "R" and "T." The powdered coal in conveyor "R" travels in the direction as indicated by the arrow and feeds the coal storage bins located at Furnaces Nos. 3 and 4. Any coal left in this conveyor after passing the coal storage bin at Furnace No. 4 is discharged at the end of the line into the dust-proof screw conveyor "S" below, which returns the surplus coal to the spout "X," and thence by gravity to the shoe of elevator "Q." With this arrangement there is little possibility of the conveying system being choked through careless operation. The powdered coal fed to conveyor "T" travels in the direction as indicated by the arrow and feeds the coal storage bins located at Furnaces Nos. 2 and 1. The storage bin at the end of the line into which this conveyor discharges eliminates the possibility of stalling the conveyor. In addition to feeding coal to the storage bins at Furnaces Nos. 2 and 1, all the coal used by the soaking pits is conveyed over this line. The dust-proof screw conveyor "U" feeds the powdered coal to the five storage bins located at each of the five double soaking pits. Each storage bin at the open-hearth furnaces and soaking pits is equipped with an automatic weighing machine, recording the weight of coal fed to each furnace, and the coal from these scales is distributed in the storage bins by the dust-proof screw conveyors "W."

From the time the coal leaves the dryer to its delivery in the furnace the whole system between these points should be dust-proof and the greatest care should be taken to prevent leakage. This should be guarded against systematically, as leaks, however small, may permit the surrounding air in the room to become impregnated with coal dust to such an extent that a serious explosion may result.

Coal, after pulverizing, should be handled in bulk. All types of aërial propulsion and transfer in the form of dust clouds should be avoided, for the reason that accidental ignition may at any time wreck the whole system.

Screw conveyors and bucket elevators equipped with dust-proof casings are best adapted to handling powdered coal in bulk. Screw conveyors of 9 inches and 12 inches diameter should not exceed 250 and 300 feet respectively, if the best results are to be expected. Where transmission lines of greater length are necessary they should be divided.

The storage of powdered coal in large or small quantities for any length of time is not advisable, owing to its tendency to fire, collect moisture, and pack.

Powdered coal in storage, containing about three-quarters of one per cent. moisture and one per cent. sulphur, will invariably fire within six days. If the moisture be increased to over one per cent. and the sulphur to four or five per cent., spontaneous combustion may occur within twenty-four hours. Probably the temperature at which powdered coal is delivered to the storage bin, and the sulphur content of the coal, influence the rate of spontaneous combustion rather than moisture.

Owing to the hygroscopic nature of dried powdered coal, long storage is not desirable.

In its normal state powdered coal is light and fluffy; after forty-eight hours' standing in storage, however, the physical arrangement of the particles produces a dense packed mass. So dense does the fuel become that one's fingers cannot make an impression even one-half inch deep. To meet ideal conditions, powdered coal should be kept in motion.

With properly designed machinery and storage bins, having twelve hours' supply placed at each furnace, the coal may be kept in motion and repairs and adjustments made before the supply becomes exhausted.

FUEL.

Low-grade bituminous coals, anthracite, lignites, and even coke breeze in a powdered form, can be burned with good results, certain types of heating furnaces now being operated with such fuels.

It should be understood that the first cost of fuel used is not the correct index by which to judge of economy when fuel must be prepared and pulverized.

Low-grade bituminous coals, being high in non-combustible content, occasion an inordinately high pulverization cost, as compared to high-grade bituminous coals. Equally, anthracite coals of highest first cost not only add to the pulverization cost on account of their hardness, but, although having little non-combustible content, their economy in actual use is not to be compared to that of the best bituminous coals, because of their high fixed carbon content, resulting in much slower ignition.

One of the disturbing factors in the use of powdered coal

is that of the large accumulations of ash deposited within the furnace, only a small proportion escaping through the stack. When using even a good grade of coal, ash will accumulate rapidly, and therefore fuel of low ash content is always most to be desired.

In obtaining the best economy in any particular case there must be a blending of plant location with the prices of available fuels of varied grades and of the results of tests conducted under operation.

Slack coal is preferable to other forms: it costs less, requires less power for pulverizing, owing to its fine state, and materially increases the capacity of the pulverizer.

While the presence of sulphur in small quantities in powdered coal has no ill effect in heating and annealing furnaces, it should be given careful attention when used in the reduction and refining of metals or ores.

Generally speaking, therefore, the fuel available for burning in metallurgical furnaces has a restricted range both as to species and quality. Only the best bituminous coals, high in volatile content and low in both sulphur and ash, are desirable.

Coal used in heating and puddling furnaces should closely approximate the following analysis:

Volatile matter	Not under 30.00
Fixed carbon	Not under 50.00
Moisture	Not over 1.25
Ash	Not over 9.50
Sulphur	Not over 1.00

In open-hearth furnaces a still better grade is desirable, a suitable analysis being as follows:

Volatile matter	Not under 36.00
Fixed carbon	Not under 52.00
Moisture	Not over 1.25
Ash	Not over 6.00
Sulphur	Not over 1.00

DRYING.

The dryer generally used for the purpose of preparing coal before pulverizing is of the revolving cylinder type, provided with an external furnace, usually equipped with an automatic stoking device.

The fuel consumption of the dryer will vary with reference to

the amount of moisture to be removed. In drying coal containing about one and one-quarter per cent. moisture, to be dried to one-half of one per cent. or less, the fuel consumption should not exceed 26 pounds per ton.

The power consumption for operating the complete drying unit, which includes the power consumed by the coal-feeding mechanism, the dust fan, the stoking device, and in revolving the dryer cylinder for a ten-ton capacity dryer, figures about one and one-half kilowatt-hours per ton of dried coal.

In the operation of the dryer care should be taken to avoid overheating, in order not to fire the coal or to drive off part of the volatile content.

If the moisture is allowed to exceed three-fourths of one per cent., operating troubles result, and these become intensified the higher the percentage of moisture.

Moist coal reduces the capacity of screen-type pulverizers, as moist coal will clog the screens. Also, the moisture in the coal governs in a large measure the tendency to pack and to arch in the storage bins, causing an intermittent flow of coal to the feeding device and the consequent loss of the one most essential factor; namely, uniform feed to the furnace.

It is easier to dry coal to one-half per cent. moisture or less than it is to maintain it in this state. This is explained by the fact that the moisture driven off from the coal in the process of drying saturates the hot air contained in the dryer cylinder. In this highly saturated condition the air follows the dried coal through the dust-proof conveying system to the enclosed storage bin. As the coal and air cool, moisture is precipitated and the volume of the air diminished, with the result that more warm saturated air is drawn from the dryer. These conditions, obviously, meet the requirements of a still of fair proportion.

The precipitation of moisture resulting from the cooling process of the coal and air may be almost entirely overcome by placing ventilating shafts on the storage bin and the high points of the conveying system connected with the outside air. Each shaft should be equipped with a ventilator of approved type, and proper provision should be made to collect and deflect any condensation in the ventilating shafts, so as to prevent its return.

It is thus evident that in the process of drying, through the medium of heat, a small quantity of the expelled moisture will

find its way back in the coal after cooling. For this reason it is good practice to gauge the dryer so that the resultant product leaving the dryer will contain less than one-half of one per cent. moisture.

PULVERIZING.

In order to obtain high efficiency of combustion, powdered coal should be reduced to a fineness so that 95 per cent. will pass a sieve of 100 meshes to the linear inch and so that 83 per cent. will pass a sieve of 200 meshes to the linear inch. Greater degrees of fineness will undoubtedly produce higher efficiency of combustion.

Machinery for pulverizing is adapted to two systems of coal-dust burning. In one system the pulverizer has a capacity sufficient for one furnace and delivers the powdered fuel directly into the burner without intermediate storage. In the other system the pulverizers have a large capacity, and one unit will pulverize enough coal to operate several furnaces, the distributing system being so arranged that the powdered coal is conveyed to storage bins, preferably near the furnaces.

There are a number of designs of pulverizing machines of merit on the market, but only one will be briefly described in this paper.

One of the pulverizers largely used is the Fuller-Lehigh mill. The material to be reduced is fed to the feeder hopper of the mill from an overhead bin by gravity. The feeder is mounted on top of the mill and has a range of three speeds; in addition, the feeder hopper is provided with a slide, which permits the operator to increase or decrease the amount of material entering.

The pulverizing mechanism consists of four unattached steel balls, which are propelled around the grinding ring by means of pushers attached to the mill shaft. Above the grinding ring and the balls is a fan having two rows of blades, one above the other. The lower set of fan blades lifts the finished product from the pulverizing zone into the chamber above the grinding ring, where it is held in suspension by means of the fan action of the upper row of blades until it is floated out through the screen, which completely encircles the separating chamber. The finished product is discharged through a spout which may be placed at any one of four quarters of the mill. All material discharged from the mill is finished product and requires no subsequent screening.

These machines are eminently suited for the production of finely ground material. They have a high mechanical efficiency and are economical in cost of installation, operation, and maintenance.

In the process of pulverizing, a large part of the heat generated is absorbed by the coal and contained air. The temperature which they attain is high enough to expel part of the moisture in the coal, while the air is of a sufficiently high temperature to establish satisfactory saturation.

The coal and air cool off in their course through the dust-proof distributing system to the enclosed storage bins, and a similar condition exists as in the case of dried coal as heretofore referred to. Similar attention must be given to ventilation; otherwise it would be a common occurrence to find water dripping from the bottom of storage bins ten or twelve hours after filling.

The pulverizers, after being shut down, sweat in cooling, and proper ventilation is the only preventive.

The power consumption of the pulverizer will vary according to quantity of output and degree of fineness of the finished product. Pulverizing mills of the type described, having a capacity of about four and one-half tons per hour, pulverizing to a fineness so that 95 per cent. will pass through a 100-mesh sieve and 83 per cent. through a 200-mesh sieve, will consume about 10.5 kilowatts per hour per ton of product.

In a plant having an average output of 200 tons of powdered coal per day the cost is as follows:

	Per gross ton of coal produced
Fuel for dryer	$0.030
Repairs, buildings, machinery, and equipment	.200
Labor	.150
Power and light	.215
Supplies	.005
	$0.600

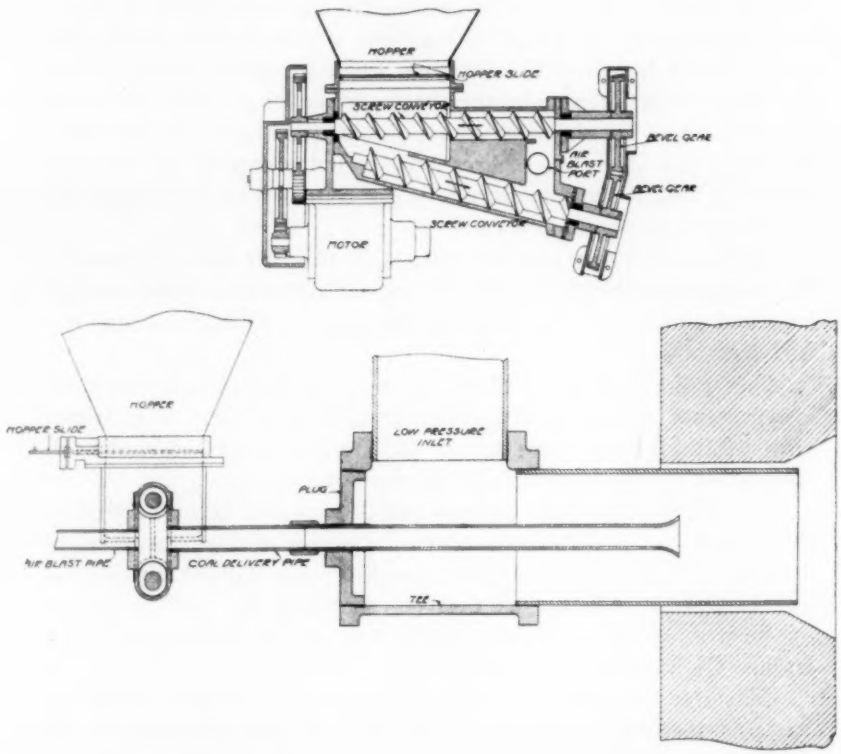
The above figures include all costs, from the receipt of the coal in the cars to its delivery in a powdered state in the furnace. No allowance has been made for overhead and depreciation.

Shrinkage in the coal becomes a prominent factor, and must not be lost sight of. It may vary from 150 pounds to 270 pounds per gross ton.

FEEDERS AND BURNERS.

Powdered-coal feeders are of two kinds—one type consisting of a mechanically operated screw or flight conveyor having a variable feed, the other type consisting of a siphon, through which the fuel is fed by the medium of compressed air, the feed being regulated by the air-pressure.

FIG. 3.



Burners for powdered fuel are operated under either low or high pressure. Low-pressure burners are used with an air blast varying from two ounces to eight ounces. High-pressure burners are used with compressed air varying from forty to one hundred pounds pressure.

Fig. 3 illustrates a sectional elevation of a mechanically operated low-pressure feeding apparatus for coal dust, also a sectional

view of the feeder taken across the air-blast ports, showing the method of its connection with the burner.

By referring to the sectional elevation it will be noted that from the hopper the horizontal conveyor screw delivers a stream of coal in the direction of the arrow mark, which falls as a continuous shower past the air-blast ports, and is picked up by a cross-stream of air, which delivers the mixture through the coal-delivery pipe to the burner.

The quantity of fuel delivered by the conveyor screw is regulated by varying the speed of rotation, which in this case is obtained through a direct connected variable speed motor. The amount of fuel taken up by the cross-current of air will vary with the pressure of the air blast, which is controlled by a suitable valve placed in the blast line. Any excess fuel escaping the feeding action of the air blast is automatically returned to the hopper by the lower inclined conveyor screw.

The coal-delivery pipe discharges its mixture into the burner, the low-pressure inlet pipe furnishing the necessary additional air for combustion, and the resultant mixture is discharged into the furnace.

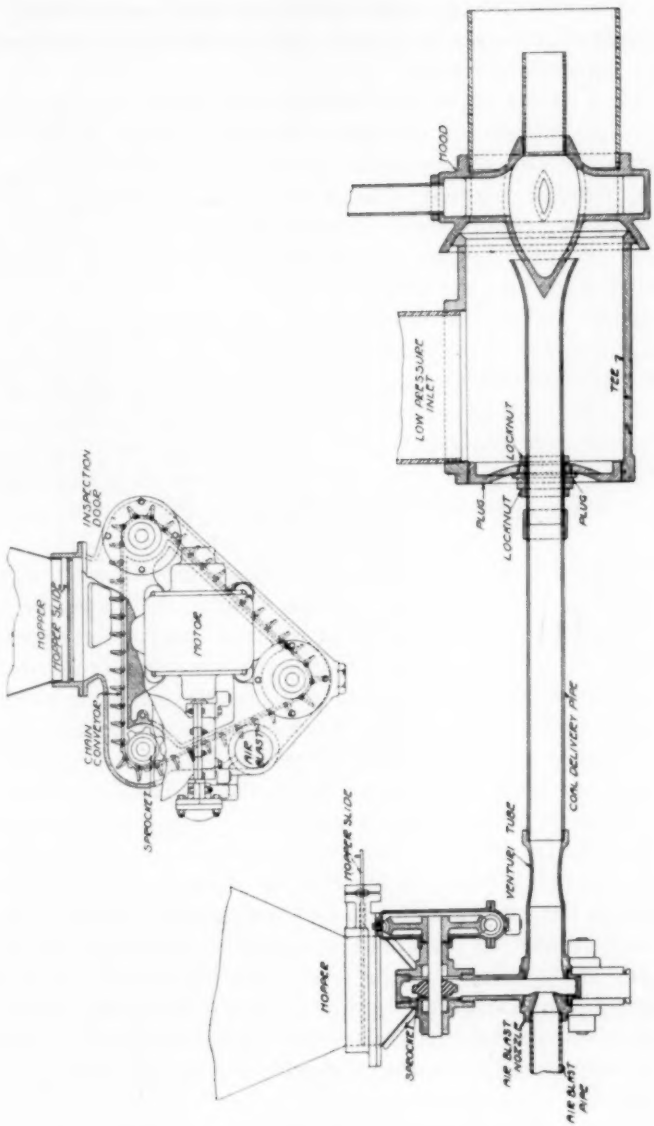
Fig. 4 shows a sectional elevation of a mechanically operated low-pressure powdered-coal feeding apparatus, also a sectional view of the feeder taken across the air-blast ports, showing the method of its connection with the burner.

By reference to the sectional elevation it will be noted that in this device an endless flight conveyor chain is used for feeding a stream of powdered coal in a continuous shower across the air-blast ports, and the excess fuel escaping the feeding action of the cross-current is automatically returned to the hopper by the endless flight conveyor chain.

Variable fuel feed is obtained through a direct connected variable speed motor, and the amount of fuel taken up by the cross-current of air will vary with the pressure of the air blast.

The air-blast inlet nozzle connecting with one side of the feeder case is reduced, the outlet side being flared, beyond which is a Venturi tube used to induce higher velocity of the mixture leaving the feeder, thereby causing a slight vacuum or pull throughout the case, the mixture continuing through the coal-delivery pipe to the burner. The cone extension on the hood of the burner enters the flared end of the coal-delivery pipe,

FIG. 4.


HOOD
LOW PRESSURE INLET
LOCKNUT
TEE
PLUG
LOCKNUT
PLUG
INSPECTION DOOR
HOPPER
HOPPER SLIDE
MOTOR
MAIN CONVEYOR
AIR BLAST
SPROCKET
COAL DELIVERY PIPE
VENTURI TUBE
HOPPER SLIDE
HOPPER
SPROCKET
AIR BLAST NOZZLE
AIR BLAST PIPE

breaking the solid shaft of coal and air and deflecting it around the inner periphery of the burner pipe. The mixture takes the form of a hollow ring, in the centre of which an auxiliary blast is discharged, giving a very thorough atomization of the particles as they enter the furnace.

Figs. 3 and 4 serve to illustrate two forms of low-pressure mechanical feeders and burners in commercial use, modifications of which are also in successful operation, all involving the same general principle; namely, a mechanism which will give a uniform and properly proportioned mixture of coal and air, both under variable control, feeding the resultant mixture in a thoroughly atomized state into the furnace.

Feeders and burners of this type are used almost exclusively on the many forms of heating furnaces in the metallurgical arts. This method of burning powdered coal with low velocity of both air and coal produces a short flame, as the fuel combusts almost the instant it leaves the burner, and the heat thus produced is conveyed by the gases from the initial point of firing with less cutting action upon the material being heated and on the brick work.

Powdered coal will flush, and when once started will run like water. Screw feeding devices should, therefore, be made very long and of a reasonably fine pitch in order to set up enough friction and baffling action to prevent the coal from flushing through the feeding mechanism and causing irregular feed.

In the case of the feeding mechanism shown in Fig. 3, long screws would make a cumbersome and expensive device, and efficiency has been sacrificed in this form of feeder for the sake of compactness and cost, as feeders of this design in use at present will invariably flood. They have another very objectionable feature; namely, if the air blast is not turned on and the feeder started up, the screws will jam so hard that the motor is stalled. The arrangement of the inlet and outlet blast through the feeder case sets up a pressure in the feeder, the result being that it not only tends to arch the coal in the bin, but it blows the coal out of the bin or the feeder case, wherever a leak may occur. In addition, under normal running it consumes considerable power to operate.

In Fig. 4 the vertical flights and the conveyor chain have a baffling action which prevents flooding. Under operating con-

ditions it has been proved that the coal will not pack in the feeder should the air blast be cut off. The air-blast nozzle and Venturi tube, producing a suction through the case, have a tendency to prevent arching in the hopper, thus giving a more reliable and

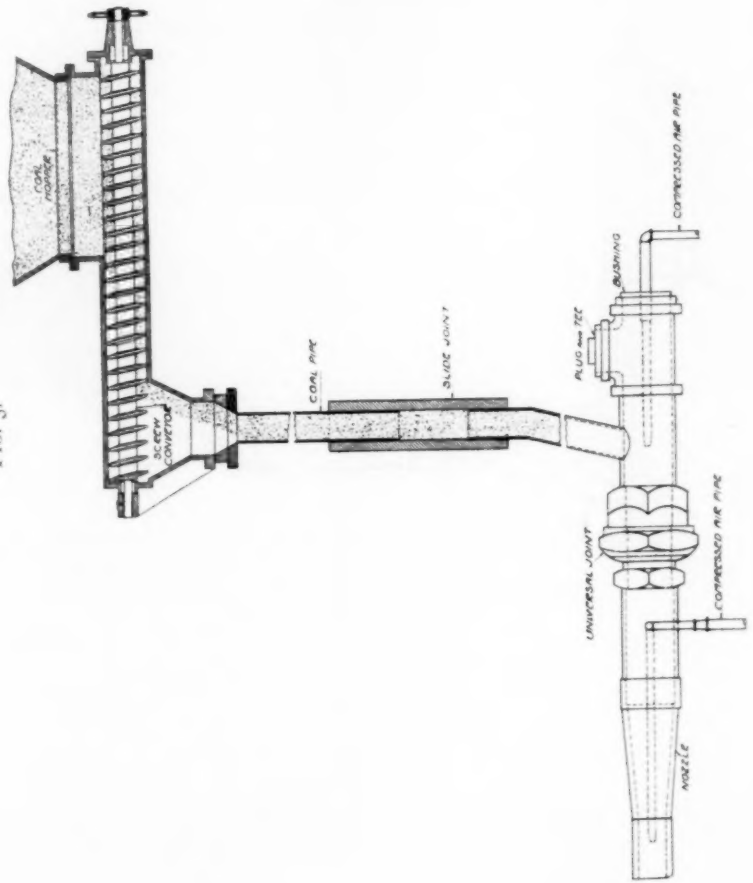


FIG. 5.

uniform feed. In addition, this suction prevents leakages, as there is always an inward pull on the case. This type of feeder takes one-tenth of the power to operate it as compared with the same capacity of screw feeding device shown in Fig. 3.

Fig. 5 shows a sectional elevation of a mechanically operated

high-pressure powdered-coal feeding apparatus. By reference to the drawing it will be noted that in this device a long screw of fine pitch conveys the coal from the hopper and discharges a uniform stream of powdered fuel into the coal pipe. This stream falls by gravity down the coal pipe and is picked up by a

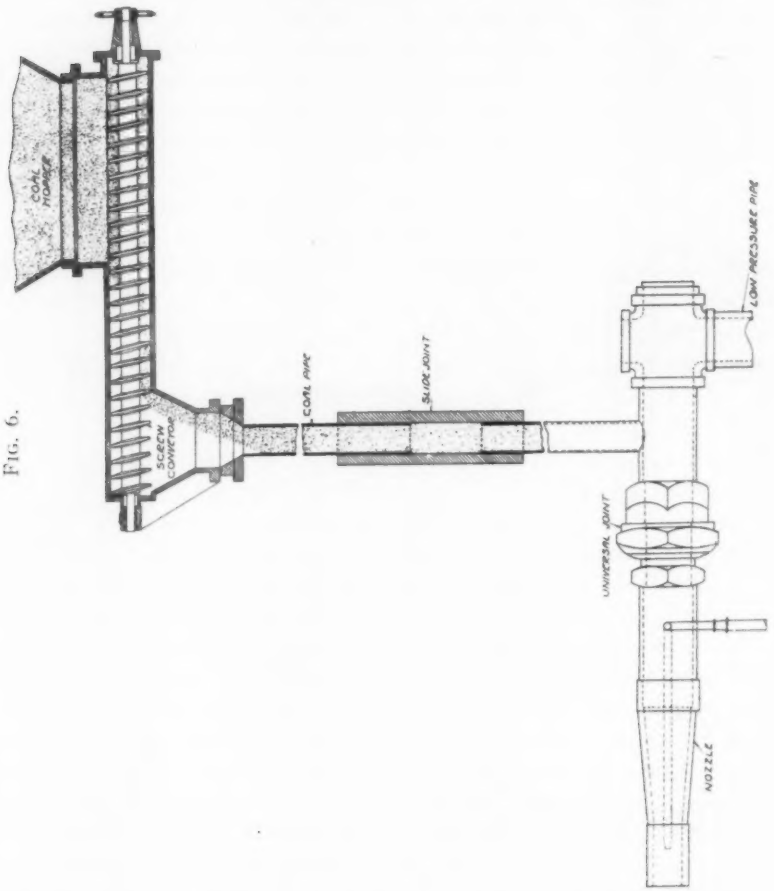


FIG. 6.

cross-jet of compressed air as it enters the burner. The expansion of the compressed air in the larger diameter of the burner thoroughly mixes the coal and air, and this mixture is injected from the burner into the furnace at high velocity by the compressed-air jet at the end of the nozzle.

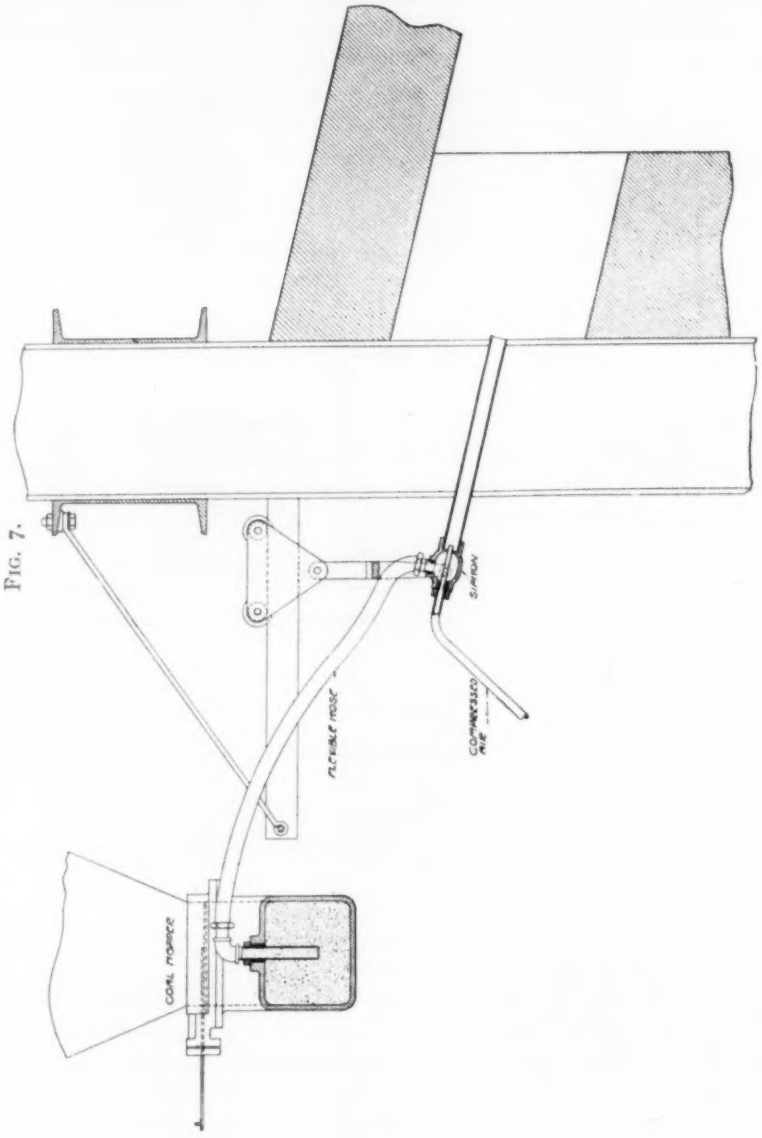


FIG. 7.

By varying the speed of rotation of the conveyor screw variable fuel feed is obtained.

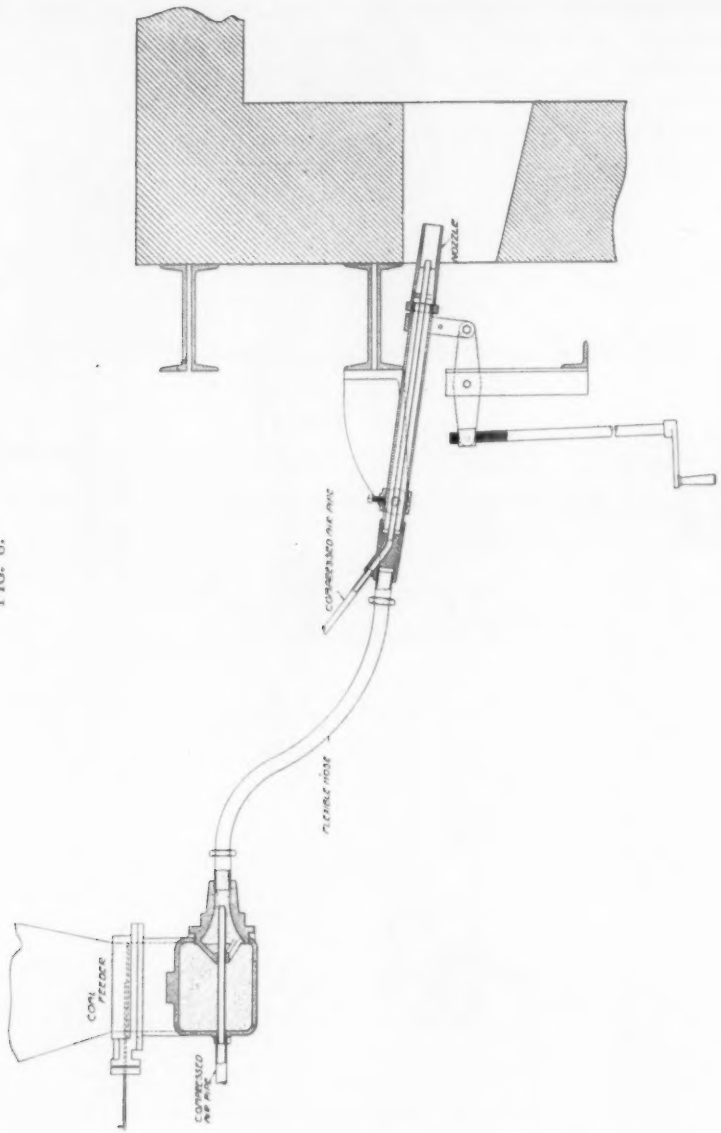


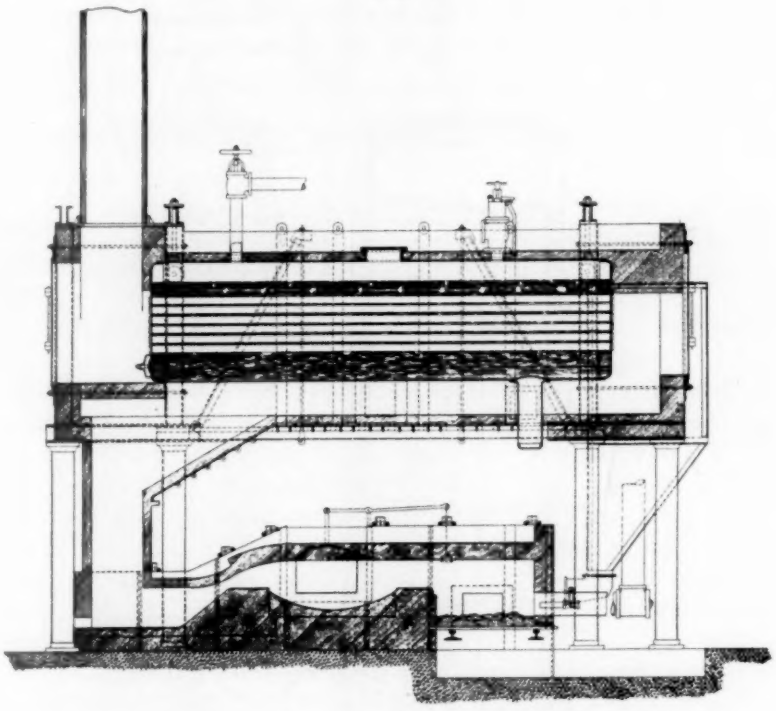
FIG. 8.

Fig. 6 illustrates a sectional elevation of a mechanically operated high-pressure feeding apparatus for powdered coal, which is similar in every respect to that shown on Fig. 5, excepting that

low-pressure air of one pound pressure is used to pick up the stream of coal delivered to the burner by the feeding device.

Fig. 7 illustrates a siphon type feeder and burner. By reference to the drawing it will be noted that the coal is siphoned from the hopper into the burner and discharged at high pressure into the furnace.

FIG. 9.



PUDDLE FURNACE

Fig. 8 illustrates another form of siphon type feeder and burner. By reference to the drawing it will be noted that a siphon is placed in the coal hopper, discharging a mixture of coal and air into the burner, and the siphon in the nozzle of the burner discharges the mixture at high velocity into the furnace.

Feeders and burners of the high-pressure type produce a long flame through progressive combustion and can be used only where the form of the furnace and the character of the work demand

that an elongated cutting flame be developed in close proximity to the work done. This method of application is adapted to open-hearth furnace practice, and ore nodulizing.

In the type of feeders and burners described it is interesting

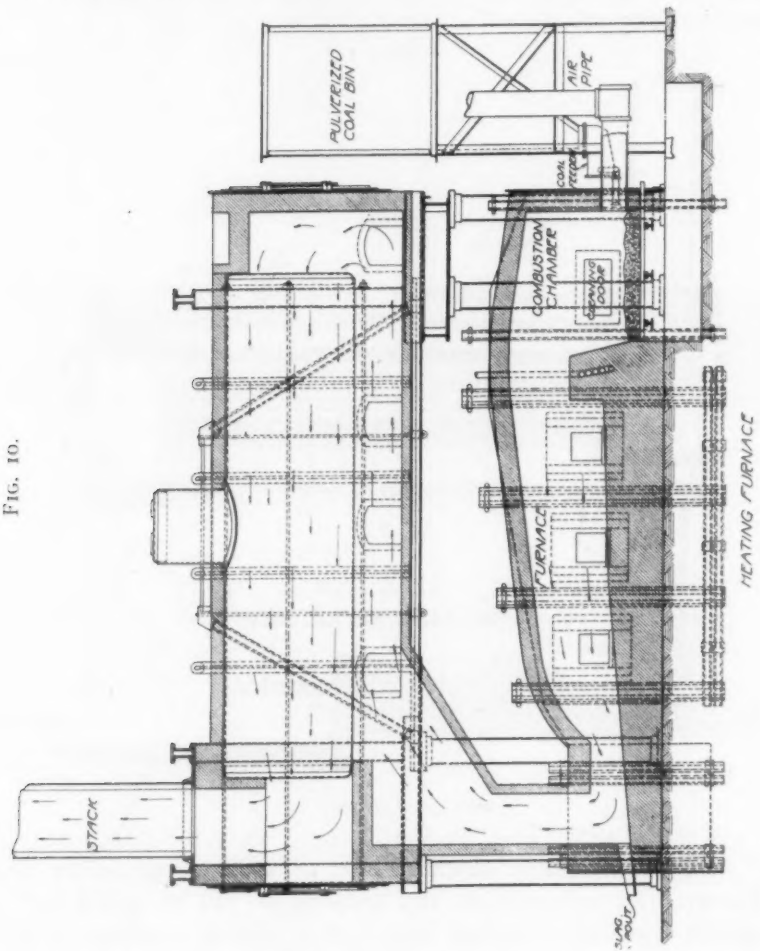


FIG. 10.

to note that the results obtained in the combustion of the fuel are equally good, whether the powdered coal is injected into the furnace from the burner at a velocity of 1500 feet per minute or of 25,000 feet per minute.

FURNACES.

In the metallurgical processes powdered coal has been applied with commercial success to various types of furnaces, such as annealing, puddling, heating, open-hearth, ore nodulizing, etc.

In order to insure success in applying powdered coal to furnaces, no matter what their type may be, one general rule must be obeyed; namely, that it be fed to the furnace at a uniform rate in a thoroughly atomized state, and that the furnace be so designed that complete combustion may take place while the coal is in suspension.

Fig. 9 shows a sectional elevation through a puddling furnace arranged with a return tube waste-heat boiler and equipped for burning powdered coal.

Fig. 10 shows a sectional elevation of a three-door heating furnace of the type generally used in heating iron piles and steel billets, also arranged with a waste-heat boiler and equipped for burning powdered coal.

In both of these installations a low-pressure burner discharges the mixture of coal and air into a combustion chamber. As the fuel combusts the heat thus produced is conveyed over the bath or furnace hearth, as the case may be, and the waste gases pass through the boiler setting to the stack.

Loose grate bars supporting a bed of about 9 inches of ash form the combustion chamber hearth, and a large portion of the ash contained in the coal collects over this surface. After each heat the accumulation of ash is raked out through the cleaning doors, and once a week the grate bars are dropped and the chamber thoroughly cleaned.

The accumulation of slag at the base of the uptake flue is tapped out from the slag runner. The ash which falls upon the material in the furnace is too small a proportion to cause any ill effect. In the boiler settings and flues considerable ash is deposited in the form of an impalpable powder, which is cleaned out once every twelve hours.

As to the economy of fuel on puddling furnaces, the use of powdered coal has shown an average saving of about 30 per cent. to 36 per cent., and on heating furnaces 15 per cent. to 25 per cent. For every pound of coal fired the waste-heat boilers show an evaporation of from seven to eight pounds of water.

Fig. 11 shows a sectional elevation of a continuous heating

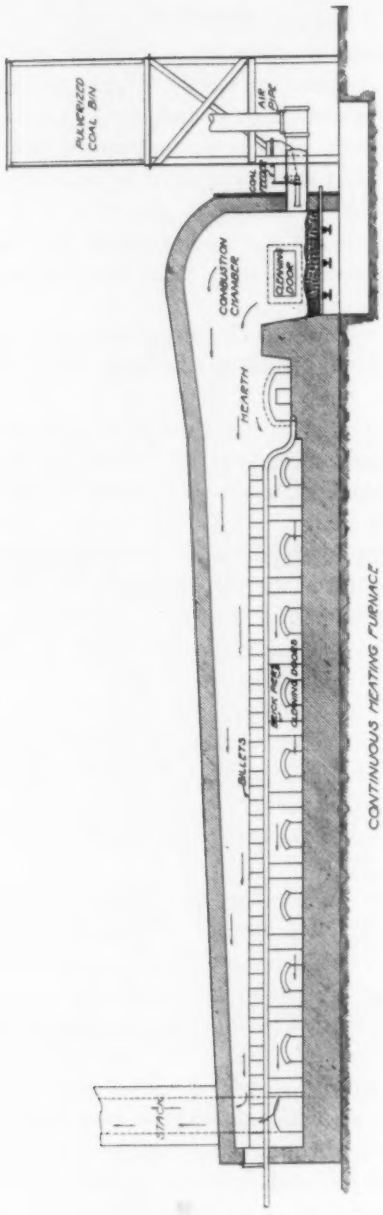

PULVERIZED COAL BIN
AIR DUCT
COAL FEED
COMBUSTION CHAMBER
CLEANING DOOR
HEARTH
BILLETS
CONTINUOUS HEATING FURNACE

FIG. 11.

furnace for heating steel billets, and equipped for burning powdered coal.

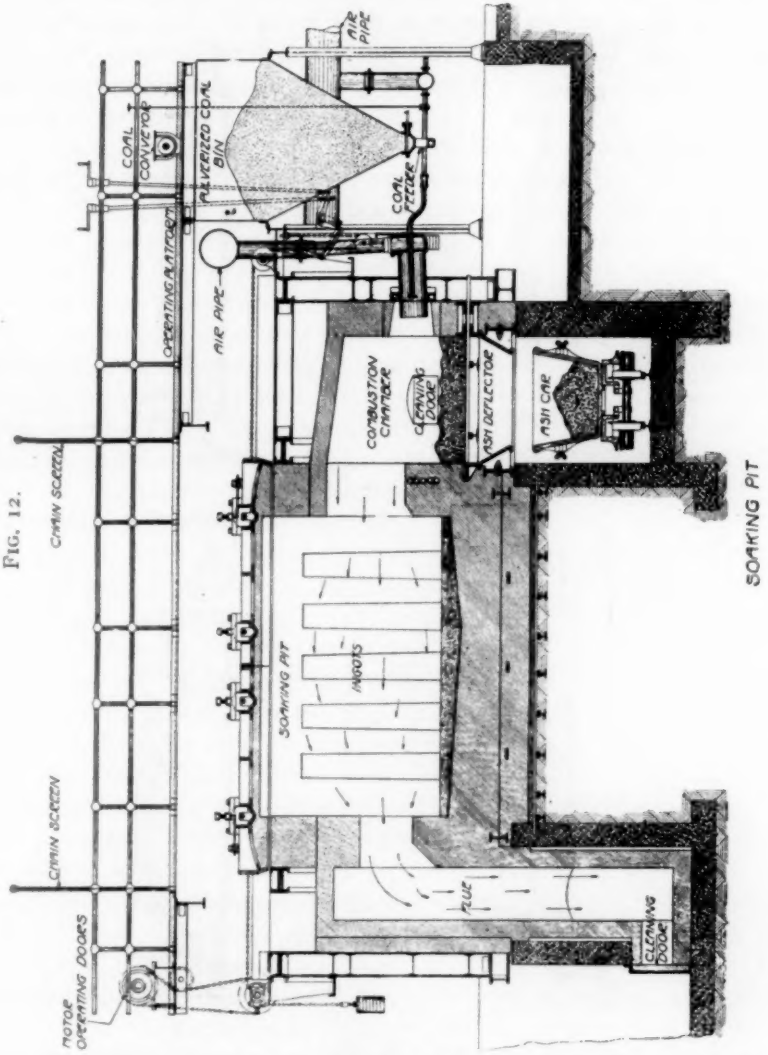


FIG. 12.

The use of powdered coal as a fuel in soaking pits represents probably the latest application of this form of fuel in the metallurgical arts. Fig. 12 shows a sectional elevation through a soak-

ing pit equipped for burning this form of fuel. The drawing clearly shows the construction, and the mode of operation will

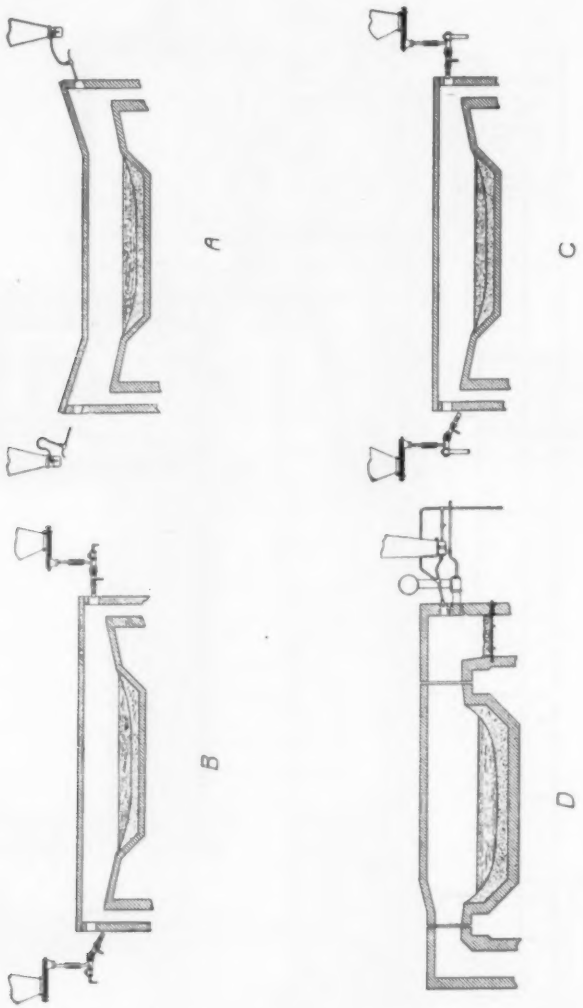


FIG. 13.

be readily understood. Five double soaking pits of the general design shown are now in operation and are giving very satisfactory results.

Another recent application of powdered coal is in open-hearth

furnace practice. At this time four different steel plants are using this form of fuel in open-hearth furnaces with encouraging results. While all the installations are more or less in an experimental stage and not as yet fully developed, owing to the limited time of application, the results obtained thus far have fully demonstrated the economy of powdered coal over oil and show equal economies with producer gas.

Fig. 13 shows the four different methods at present employed for applying powdered coal to open-hearth furnaces.

A, B, and C represent installations in which high-pressure siphon type burners are used, similar to those shown in Figs. 5, 6, and 7. One burner is placed on each end of the furnace, the fuel being reversed as in the case of producer gas. As the gas flues are eliminated in this process, the regenerative chambers in most cases have been enlarged, and in place of checkers staggered arches or parallel walls have been built to give the necessary regenerative area. There are at the present time one 75-ton, three 60-ton, and four 35-ton open-hearth furnaces of the regenerative type in operation, with modifications in the construction of the regenerative chambers as described.

At one plant the results obtained have been so encouraging that a second furnace of 75 tons capacity is now under construction.

D represents a somewhat radical departure from the old-time theories of open-hearth furnace practice. By reference to the diagram it will be noted that the burners are arranged only at one end of the furnace, the path of the flame being always in one direction. There are no regenerative chambers, air at room temperature being used for combustion of the fuel.

The theory underlying this method of applying powdered coal to open-hearth furnaces is:

First, the fuel is burned above the bath, and all the heat contained in the coal is instantly developed in the furnace.

Second, as the path of the flame is in one direction, all parts of the furnace are maintained at the same temperature.

Third, by reason of their high radiating capacity, the infinite number of minute incandescent particles in the powdered coal communicate the heat by radiation,

and not by convection, thus eliminating the necessity of bringing the surrounding air to the temperature of the coal particles.

Fourth, all the heat in the waste gases is conserved and used in the production of steam.

The extra fuel consumed, due to the use of cold air, is offset:

First, by the elimination of all loss in the gas producer process.

Second, by the elimination of all loss due to frequent reversals.

Third, by the elimination of all loss in waste heat taken up by the regenerative chambers.

Fourth, by the elimination of the expensive maintenance cost of producer plant and regenerative chambers.

Fifth, by the greatly reduced first cost of installation.

Fig. 14 shows a sectional elevation of this furnace. A section through the combustion chamber looking towards the back wall is shown in the upper left-hand corner. By reference to this view it will be noted that three burners are employed—the central one of the high-pressure siphon type shown in Fig. 8, the two side ones of the low-pressure type shown in Fig. 4.

As powdered coal requires a high temperature for ignition and maintained combustion, there would be no incentive for the powdered fuel to ignite in the cold furnace after charging, especially since the air necessary to support combustion is also cold.

The combustion chamber in this installation is maintained at a high uniform temperature at all times by the two low-pressure burners. The high temperature maintained in the combustion chamber preheats the air furnished to support combustion, and, as the high-pressure siphon burner discharges the powdered coal through the hot zone of the chamber, complete combustion of the fuel is insured.

Auxiliary air for combustion is admitted through the back wall of the combustion chamber at the roof line.

The accumulation of ash in the combustion chamber is raked out through the cleaning doors after every heat and is discharged through a trap door in the charging floor into the ash car below.

From a metallurgical standpoint, the deposit of ash on the bath is too small an amount to be noticeable.

In the slag pocket at the bottom of the vertical flue the ash and the brick slag form a thick, pasty mass, the tough consistency

of which makes its removal difficult. Beyond this point the ash settles in the flues as an impalpable powder. After each heat it is stirred up by inserting a compressed-air jet through the separate

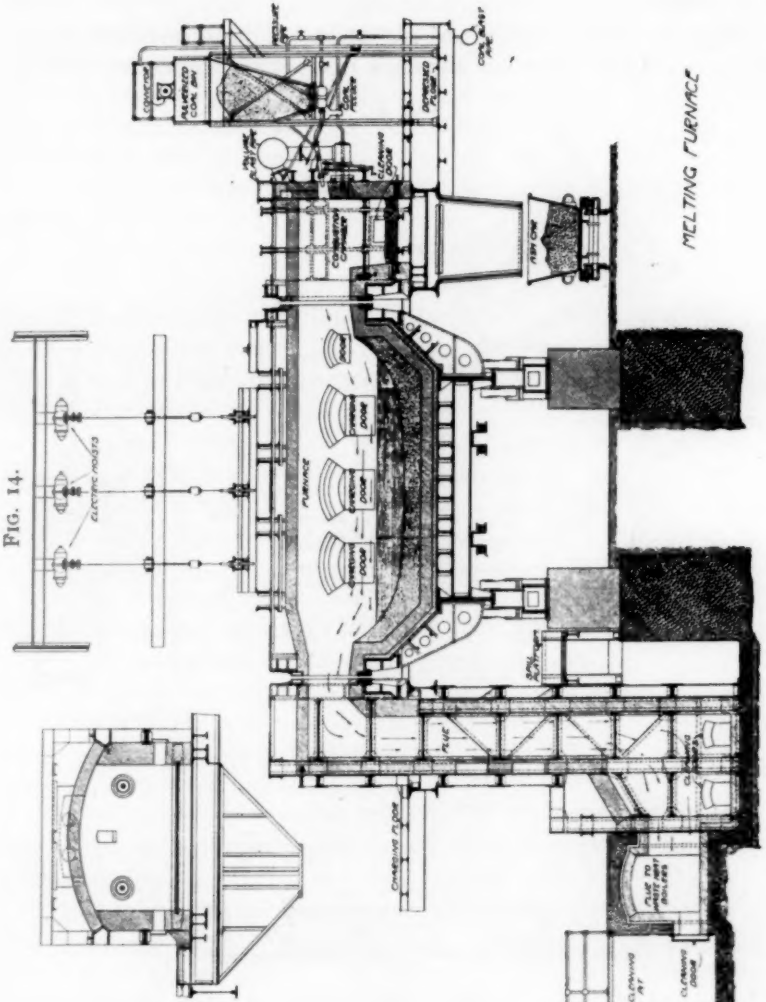


FIG. 14.

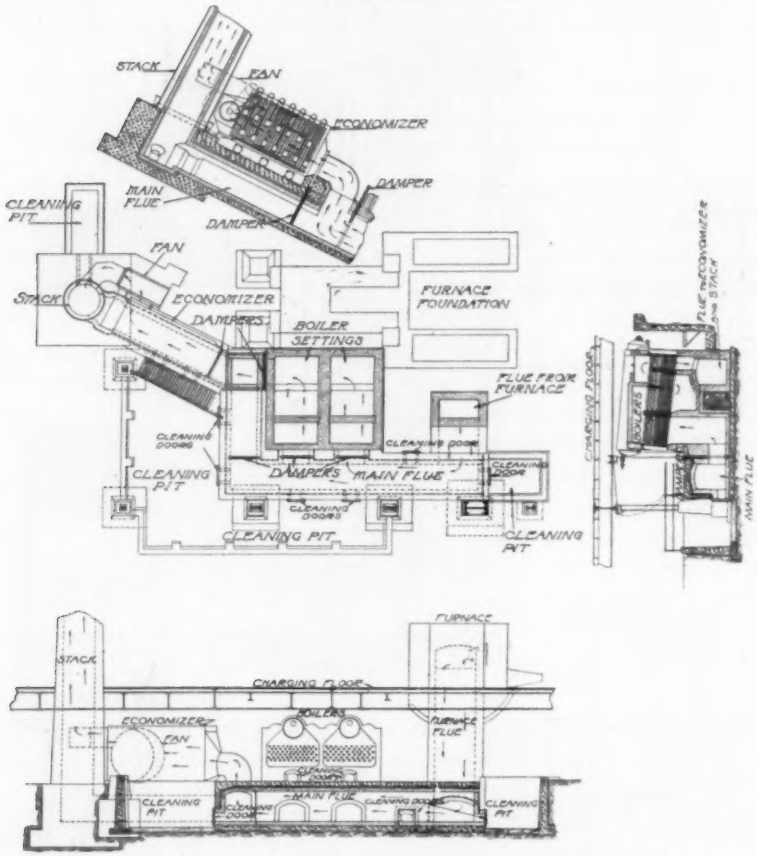
cleaning doors of the flues. The ash clouds thus produced are picked up by the flue draught and are carried in suspension out of the stack.

The boiler tubes are cleaned with steam blowers four times each day.

The course of the waste gas is indicated by the arrow marks, and is shown discharging into the flue connecting with the waste-heat boilers.

Fig. 15 shows a plan and elevation of the waste-heat plant, also a sectional elevation through the boilers and economizers.

FIG. 15.



The course of the waste gases can be followed by the arrow marks, and the general operation will readily be understood by reference to the drawing.

It will be noted that by the arrangement of the flues and

dampers the whole waste-heat plant may be by-passed. The economizer and both boilers may be by-passed either separately or in combination, as desired. The flexibility of this arrangement permits any adjustment or repairs to the boilers or economizers without affecting the operation of the furnace.

Within the past few months four 50-ton basic open-hearth furnaces thus arranged have been placed in operation. In this short period operating conditions have demonstrated the soundness of both the underlying theory and the engineering principles involved in this method.

Compared with producer gas, equally high temperature is attained.

Uniform temperatures throughout the furnace are maintained.

Heats can be made within reasonable time.

Fuel consumption is high. This, however, is offset by the fact that the waste-heat plant produces an average evaporation of six and one-quarter pounds of water per pound of coal fired in the furnace.

Compared with the best boiler-room practice, 62½ per cent. of the fuel consumed by the furnace is used in the generation of steam, leaving 37½ per cent. chargeable to steel production. Based on this reasoning, economies over oil and producer gas are fully substantiated.

In the use of powdered coal in metallurgical furnaces we have arrived at a stage of development where fixed rules may be laid down for its application which, if strictly followed, will result in high economy and efficiency.

The personal equation is the important factor in operating part of the apparatus as developed thus far. It is necessary to depend too greatly upon this uncertain element.

In the drying process the operator may at any moment upset the complete equilibrium of a plant either by overheating the coal or by not drying it enough.

In the furnace operation three or four separate adjustments are required, depending on the burner used, each adjustment bearing a fixed relation to the others. These adjustments are: The control of the coal feed, the control of the coal blast, the control of the volume blast, and the control of the furnace draught, where mechanically operated low-pressure feeders and burners are employed, all of which controls are separately left

to the judgment of the operator. When we consider that there is no fuel so sensitive to correct application as powdered coal, and when we realize the exact precision required in its manipulation, the dependence placed on the personal element is at once apparent.

In order to obtain uniform conditions, it is necessary to eliminate the personal equation as far as possible. In the drying process this might be accomplished by an automatic control of the coal feed governed by the temperature of the dryer cylinder. In the case of the burners and feeders this might be done by a single adjustment regulating and supplying the correct proportion of air and coal, with provision for adjusting the air and coal independently in order to obtain correct proportions for different grades of fuel, thus producing an absolutely uniform combustible mixture, which will be maintained, regardless of the quantity supplied, after once setting the adjustment.

The high economy and efficiency of powdered coal in the metallurgical processes, under the limited application of this fuel and the limited development of apparatus, provide an index of its possibilities under more general use. With a further development of apparatus this form of fuel doubtless will eventually supplant oil, tar, and producer gas in the varied fields where they now hold supremacy.

THE DETERMINATION OF THE CONSTANT OF A SOLENOID.*

BY

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WHETHER measuring the earth's magnetic field by means of an earth inductor or the field in the slit of a radially divided toroid by means of a few turns of wire, the exploring coil has become a useful adjunct in measurements of magnetic field intensities. Particularly is this true since the advent of sensitive moving coil galvanometers. In order to know a magnetic field completely, both its intensity and distribution must be determined. Of the varied and many means at our disposal for thus mapping out a magnetic field, perhaps none lends itself so readily to both field intensity measurements and topographical surveys as does the exploring coil. This adaptability is well illustrated in the following special application:

TESTING THE CONSTANT OF A SOLENOID.

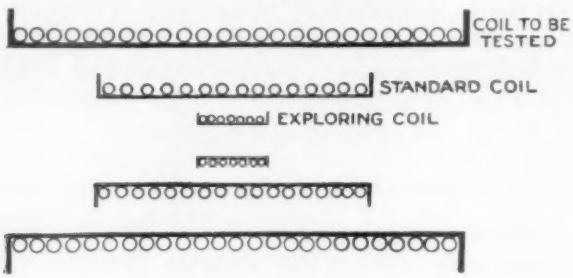
The constant of a solenoid which has been carefully wound may be found with considerable accuracy from its dimensions, so that experimental tests on the constant may be checked up very closely. Even with the greatest care in winding we are always glad to avail ourselves of any means that will assure us whether any short circuits have occurred during the winding. In other words, we want the satisfaction which comes from contemplating, side by side, the calculated and observed values and finding that they agree.

After winding several solenoids and attempting to verify their constants experimentally by various means, I have found the following method a very practical one. It is based on an old method, common to many laboratories, in which a magnetometer needle is placed at the centre of two coaxial coils, one of which is a standard coil and the other the one to be tested, and

* Communicated by the author. Read by title before the Ohio Academy of Science, Columbus, Ohio, November 28, 1914.

the deflections compared when the fields of the two coils reinforce and when they oppose each other. In the measurement of magnetic fields we may make use of the principle that a magnetometer may be replaced by an exploring coil in circuit with a ballistic galvanometer. We thereby gain all the advantages which a moving coil galvanometer offers over a moving magnet type, chief of which is the freedom from magnetic disturbances. In the above magnetometric method referred to, therefore, we may replace the magnetometer by an exploring coil in circuit with a ballistic galvanometer. In the case of testing a long solenoid, whose inner diameter is very small, the magnetometer is practically out of the question. One solenoid which the author wound was 100 cm. long and had an inner free diameter of 2.54 cm. Not only did the small inner diameter necessitate a very short sus-

FIG. 1.



pending fibre for the needle of the magnetometer, but the deflections of the needle could not have been read with any accuracy, since the magnet must necessarily be placed at the centre of the long, narrow opening of the coil.

With the exploring coil replacing the magnetometer (Fig. 1), let the two coaxial coils, centred at the same point, be connected in series and the current, I, flowing through them so directed that the fields reinforce each other. If S is the constant of the solenoid and G that of the standard coil, then when the current is suddenly broken in the circuit the induced electromotive force in the exploring coil will set up a current through the ballistic galvanometer such that its deflection, d_2, will be given by the relation:

$$IS + IG = kd_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where k is a constant dependent upon the ballistic galvanometer.

By reversing the current in one coil and not in the other and again suddenly breaking the circuit, a deflection, d_1, is obtained such that

$$IS - IG = kd_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where the field of the coil, G, has been reversed. Dividing equation (1) by equation (2) and solving for S, we obtain

$$S = G\,\frac{d_2 + d_1}{d_2 - d_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

which is the constant of the solenoid in terms of the constant of the standard coil, and the deflections of the ballistic galvanometer for the two conditions. It will be noted that so long as the current remains constant the current I does not enter into the computation, neither does the constant of the ballistic galvanometer. For measuring the current through the coils all that is needed is an ammeter which will indicate that the current is constant when the fields reinforce and when they oppose each other. When the current is supplied from a storage battery it is easily kept constant enough.

Equation (3) should apply whether the field through the exploring coil is changed by suddenly breaking the electric current or by suddenly rotating the exploring coil through 180 degrees. For a solenoid with a large inside diameter, the author feels that the rotating exploring coil may be used to advantage, as by its use the solenoid circuit does not need to be disturbed for a series of readings and the integral electromotive force is also double that obtained when the field is simply made zero in the coil. Both the rotating and fixed types of exploring coil were used in testing a coil employed in previous work [1] and no difference in results greater than experimental errors could be detected.

The question may be raised, Why determine the constant of a solenoid [2] in terms of another coil whose constant is ordinarily obtained from its dimensions, although not necessarily so? In the experiment on which this work is based, a tangent galvanometer coil was used for the standard coil, and we may answer

[1] *Phys. Rev.*, vol. 34, p. 40, Jan., 1912.

[2] By a solenoid is meant a coil whose constant is computed by the formula,

$$H = 4\pi nI\,\frac{l}{\sqrt{l^2 + r^2}}$$

the above question by saying that the constant of the tangent galvanometer coil is easily computed and not so much risk arises in the winding that there will be short circuits. Furthermore, if the constant of the solenoid determined in terms of the constant of the tangent galvanometer coil does check with that obtained by computations from the dimensions of the solenoid, we feel a greater confidence that the value of the constant we have found is the correct one. There are, however, objections to the tangent galvanometer coil as a standard. These are: (1) the field at the centre is not uniform enough over a sufficiently large space at its centre and (2) errors in measuring the dimensions creep in too easily. The first objection may be overcome by using a Helmholtz coil, but objection (2) holds even more strongly for the last type of coil. Watson,[3] in measuring the horizontal component of the earth's magnetic field, used a Helmholtz coil, and, in order to obtain an accuracy of one part in 10,000, used a coil 60 cm. in diameter and measured the radius down to 0.003 of a centimetre. This size of a coil is inconvenient to use as a standard in this work, and a smaller coil decreases the accuracy of the work.

If we examine the formulæ for the constants of various types of coils we find that the one used in computing the constant of a solenoid has fewer quantities which are affected by the dimensions of the coil. The formula is practically dependent only on the number of turns, n, per unit length, which, as will be shown later, may be made very accurate. Accordingly it was thought advisable to adopt the solenoid type of coil as a standard, making the diameter of the same as small as practical and placing it inside of the solenoid or coil to be tested. From equation (3) it is evident that so far as theory goes the standard coil may be made coaxial either outside or inside the other coil.

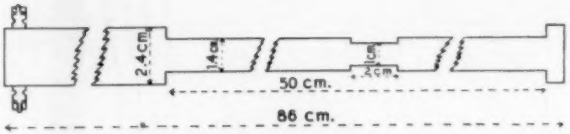
In the work as actually carried out the standard coil was made up in the following form: a rod of non-magnetic "Bakelite,"[4] 86 cm. in length and 2.4 cm. in diameter, was turned down in a lathe so as to form a spool at one end, whose length was 50 cm. and diameter 1.4 cm. (see Fig. 2). At the middle of this long spool another channel was cut out 2 cm. long and

[3] *Phil. Trans. Roy. Soc.*, p. 432, vol. 198, 1902.

[4] Specimens of hard rubber showed magnetic properties.

2 mm. deep. In this smaller channel 600 turns of No. 37 silk-covered copper wire was wound and the ends carried along in a groove to two binding posts at the end of the " Bakelite " rod. This secondary or exploring coil was covered with hard wax and smoothed to the same diameter as the spindle, which was 50 cm. long, on which the primary was to be wound. The rod was cleaned as thoroughly as possible to free the surface from any particles of steel which might have stuck in turning down the rod in the lathe. For the primary, No. 18 double cotton-covered copper wire was used and wound in four layers, which just filled the channel turned out for the primary. As each layer was put on it was thoroughly shellacked. The winding was done on a lathe and all parts of the wire and coil were kept from contact with the iron parts of the lathe. The screw-cutting attachment was adjusted so that the wire, as it was fed onto

FIG. 2.



the coil, was carried along at the same rate as the windings of the coil. While the number of turns for each layer was not the same, yet this arrangement for feeding the wire to the coil gave the number of turns per centimetre in each layer with good uniformity. There is no question but what the method employed by Jenkins [5] and others in winding solenoids gives greater uniformity in the number per unit length than the method employed in this work. Jenkins accomplished this end by cutting an accurate thread along an insulating tube and winding bare wire under tension in this groove. Inasmuch as I wanted a standard coil of several layers, this seemed impractical unless the coil could have been built out of a series of telescoping " Bakelite " tubes. The small inner diameter of the solenoid to be tested prevented the use of more than two tubes.

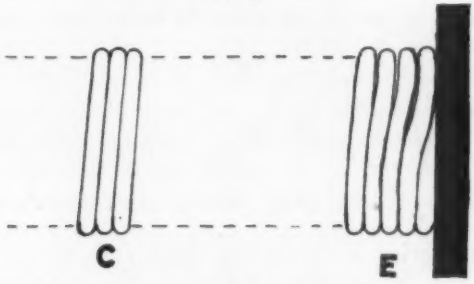
The constant of the standard coil was computed by means of the well-known formula [6] already given for solenoids. The

[5] Jenkins, *Phil. Mag.*, Ser. 6, vol. 26, p. 752, 1913.

[6] Watson, "A Textbook of Practical Physics," p. 522, 1906.

total field strength was taken as the sum of the fields due to the various layers. For a long time there was a persistent difference between the computed and observed values of the solenoid tested. In the case of the solenoid, one metre in length, this difference amounted to about one-half of one per cent. and was always in a direction such that the computed value was less than the experimental. After investigating, seemingly, every possible chance of error, I finally found, what apparently has been overlooked in many important researches, that in the various coils which were tested, n, the number of turns per unit length, was invariably greater at the centre than at the ends. This is, I believe, due to the fact that as the wire comes from one layer up to the next one at each end of the coil in the wind-

FIG. 3.



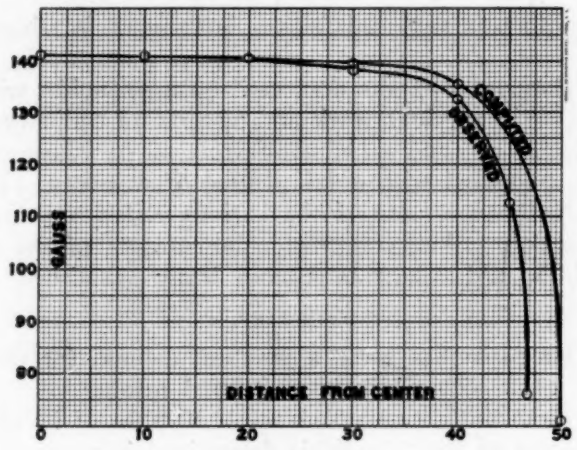
ing, the turns which lie next to the wire where it comes up must curve out around it, and in so doing cannot be made to lie so close together as at the middle of the coil where the turns have straightened out (see Fig. 3). Ordinarily we divide the total number of turns in a layer by the length of the layer in order to find n. This leads to a systematic error, as indicated above, if, as I have found, the value of n is smaller at the ends than in the middle of the coil.[1] The turns at the ends do not have so much effect on the field at the centre as those turns wound about the centre, and therefore they should not be given equal weight with those at the centre when it comes to finding the value of n. The correction for this discrepancy was made by finding n for various parts of the coil and then the average when these various values of n had been weighted proportional to their

[1] This effect is very noticeable in the windings of the field coils on older types of dynamos; in fact, it must be present in every solenoid as ordinarily wound.

effects upon the field at the centre of the coil. When this was done the computed and observed values of the field at the centre of the coil agreed within the limits of accuracy of the method, which was 1 : 1000. The fact that the value of n was less at the ends of the coil than at the centre may be shown in another way. If the observed values of the field intensity along the axis of the coil are compared with the computed it will be found that the observed values drop off more rapidly than the computed as one passes from the centre out toward the ends. This is shown in Fig. 4.

The large solenoid to be tested, of which mention has already

FIG. 4.



been made, was wound in 24 layers and had a total of 11,251 turns. It was wound on a brass tube, 2.54 cm. inner diameter and 3.8 cm. outer diameter. This tube, with its end pieces, was slotted lengthwise to prevent induction currents when alternating currents were sent through the coil. The computed constant was obtained in the manner just indicated and found to be 142.362 gauss, while the value as determined experimentally was 142.445. The last value was the average of twenty observations. This difference means a discrepancy of less than one part in a thousand between the observed and computed values, which for this particular coil means that not more than 10 to 15

turns could be cut out by a short circuit without being able to detect it. However, by refinements which have been indicated, such as methods of winding and construction, greater accuracy can be secured, and there seems to be no reason why the accuracy could not be pushed to one part in 10,000 (1 : 10,000). It would seem that in the end the accuracy of the method rested upon what refinement could be made in detecting changes in the current which flowed in the two coils. The best instrument which I had could be read only to one part in one thousand (1 : 1000). It is to be noted that in this method it is not a matter of reading the absolute values, but merely detecting variations.

The ballistic galvanometer was a Leeds & Northrup instrument, type HB, having a resistance of 18 ohms, a period of deflection equal to 9 seconds, and whose sensibility is 122 megs. It seemed to be a very satisfactory instrument for this kind of work.

The standard coil was next used on a solenoid[8] which had seen service in previous work and also on an ordinary tangent galvanometer coil and a Helmholtz coil, all of whose constants could be computed with a fair degree of accuracy. Thus not only were the constants of the various coils ascertained with greater certainty, but, conversely, the constant of the standard coil could be said to have been more firmly established.

SUMMARY.

1. This paper has given a practical method for testing the constant of a solenoid by experimental means.

2. The method recommends itself because of its simplicity. The constant of the solenoid is determined in terms of the deflections of a ballistic galvanometer and the constant of another coil taken as a standard. If a long, slim solenoid is used for the standard, the only quantity which must be known with great accuracy in determining its constant is the number of turns per unit length. The constant of the ballistic galvanometer does not need to be known, neither does the ammeter, which indicates the constancy of the current in the coils, need to be calibrated. Even the exploring coil does not need to have its inductive area determined. Once the constant of the standard coil has been definitely fixed, the method could not be much simpler.

[8] *Phys. Rev., loc. cit.*

3. It is evident that the exploring coil could have been placed first in one coil and then in the other and the deflection observed when only one field was suddenly reduced to zero. In such a case,

$$S = G\frac{d_2}{d_1} \qquad (4)$$

This last equation appears simpler. The author believes, however, that by keeping the two coils in series it will be easier to keep the current constant, because there is absolutely no change to be made in the circuits except to throw a reversing switch for one coil. Using the coils separately would necessitate change of circuits; also keeping the coils in series insures that in breaking the circuit the field due to both coils must vary simultaneously. Of course, difference in rate of decay of the magnetic fields should not affect the results if the period of deflection of the galvanometer is large enough.

4. An investigation as to what ratio of S/G would give the least error in S shows that when $S/G = 1$ the error in S should be a minimum. This is an impossible condition, as the d_1 in equation (2) becomes equal to zero. If the experiment is worked as a zero method it would be necessary to have each coil on a separate circuit and so arranged that the two fields could be made to just neutralize each other. When this occurred there would be no deflection of the galvanometer and equation (2) would then be written:

$$I_1S - I_2G = 0$$

$$S = G\frac{I_2}{I_1}$$

This was tested out, but was not so sensitive as the method finally pursued. In this zero method it would be necessary to know the absolute value of the current, which would mean the calibration of one or two ammeters.

5. This work has shown that great care must be used in winding a solenoid if the constant is to be obtained by computation. The author would recommend concentric "Bakelite" tubes where several layers are to be employed, and the winding carried out similar to the method used by Jenkins.[9] If the constant of the solenoid is to be determined by the method sug-

[9] Jenkins, *loc. cit.*

gested in this paper, then the winding need not be carried out with such extreme care.

6. Investigating the constant of a solenoid has brought out the fact with renewed earnestness that what we work with in a great many experiments is not a uniform field all along the axis of the solenoid, but, as shown by Fig. 4, it is a field that is continually decreasing as one goes from the centre of the coil out toward the ends. In work of measuring the magnetic properties of various substances this is too frequently lost sight of, and in studying such phenomena as the magnetostrictive effects everyone seems to have fallen into the error of considering the value of the field strength at the centre of the solenoid as holding constant very nearly to the ends. A consideration of the equation for the field strength at any point along the axis of a solenoid will soon convince one of this point, viz.,

$$H = 2\pi nI\left[\frac{D+\frac{l}{2}}{\sqrt{(D+\frac{l}{2})^2+R^2}} - \frac{D-\frac{l}{2}}{\sqrt{(D-\frac{l}{2})^2+R^2}}\right]$$

where D is the distance from the centre of a solenoid of length l and radius R. It was from this equation that the computed values for Fig. 4 were obtained.

So far as the author knows no one has done in a practical way for solenoids what Maxwell did for galvanometer coils, viz., determine what the form of a coil should be in order to get certain desired fields. At present work is being done on this problem. It seems quite certain that the field may be kept up to a constant value along the axis much farther from the centre than is now done by ordinary solenoids

In closing, expressions of appreciation are due Mr. Ray Calhoon, an advanced student in the department, for the valuable assistance rendered in making long and tedious series of observations.

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VICTOR MEYER—HIS LIFE AND WORK.*

BY

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I. HIS LIFE.

MODERN chemistry, little more than a century old, shows four outstanding landmarks in its evolutionary course: (1) the Foundation Period, with its eye to quantity (as represented by Lavoisier and Berzelius); (2) the Classification Period, with its basis in system (Dalton and Mendeleeff); (3) the Physico-chemical Period, with mathematics as its corner-stone (Arrhenius, Van't Hoff, Ostwald); and (4) the Period of Radio-activity—the outcome of the discovery of radium (the Curies, Thompson, Rutherford). Early in its onward march the science came to be divided into two fields: the inorganic and organic. Between the first and second periods the latter was distinctly subordinate to the former. The pioneer work of Liebig and Wöhler, who showed connecting links between chemistry and the sciences of botany, agriculture, and physiology, quickly swung the pendulum in the direction of organic chemistry; so that we find that between the second and third periods the "organicists" were not merely in the ascendency, but had all but well-nigh supplanted the "inorganicists." Then came a totally new era with the entrance of mathematics upon the scene. Many entered the new school. Some, however, under the leadership of Fischer, turned their attention to the application of chemistry to physiology; others, following in the footsteps of Perkin and Baeyer, began to build up the chemistry of commerce.

Victor Meyer, the subject of this sketch, belongs to the school of pure organic chemists—to the period when organic chemistry was in its ascendency. He easily takes his place among the foremost pioneers in this phase of the science. He began work when the superstructure of organic chemistry had yet to be built up, and in this building process few can claim the share he can. When the beauty and symmetry of the building was all but apparent Meyer passed away. The man of forty-nine [he had reached

* Communicated by Dr. Joseph S. Hepburn.

that age when he took his own life], with the rare mind that was his, could still have accomplished much.

Meyer * was born in Berlin on September 8, 1848. His father, a prosperous Jewish merchant and a man of high intelligence, surrounded himself with the *élite* of the intellectual element of the city. The chemist Sonnenschein, then a *privatdocent* at the University; Bernstein, the founder and editor of the *Volkszeitung;* Franz Duncker, Love-Kalbe, Major Beitzke (author of the "Thirty Years' War"), Schulze-Delitzsch, and Berthold Auerbach were frequent visitors to the house. It was in such an atmosphere that Victor Meyer was brought up.

Together with his brother, Victor received his earliest instruction from his mother. Later a private tutor prepared the children for the gymnasium, and this Victor entered when he was ten years old.

During these early years at the gymnasium, Meyer's leanings were rather towards literature than science. The drama especially had a strong attraction for him. Indeed, at fifteen, the boy had quite made up his mind to become an actor. To his father's remonstrances, who watched these developments with much perturbation, Victor replied: "Never can I become anything else—never! I feel it. In any other profession I shall remain a good-for-nothing the rest of my life."

However, in the meantime the lad continued his academic studies, and in the spring of 1865 he passed his matriculation examination (*Abiturientenexamen*). Hoping against hope that possibly the University atmosphere would tend to direct Victor's thoughts in another direction, the family persuaded the youth to proceed to Heidelberg, there to attend some lectures in the company of his elder brother. What the incessant arguments of the parents and friends had failed to do, the chemical lectures of one of the professors easily accomplished. In Bunsen the young man encountered one of those rare minds who can see and demonstrate the beauty and poetry of anything they happen to be engaged in.

* For much of my material I am indebted to Richard Meyer's Life of his brother.[40] Carl Liebermann's Memorial lecture delivered to the Fellows of the German Chemical Society[41] is a beautiful homage to a departed friend. Professor E. Thorpe, in his Essays on Historical Chemistry,[42] has an interesting article on Victor Meyer.

From the lips of Bunsen chemistry issued forth as a song to Nature, and as a song to Nature Meyer caught the refrain.

Small, and quite childish in appearance, the seventeen-year-old boy enrolled as a student of the University. During the first semester he attended Hofmann's lectures in Berlin, so as to be near his parents. After that he took up his abode in Heidelberg. Here he followed Kirchhoff's lectures on physics, Kopp's on theoretical chemistry, Helmholtz's on physiology, Erlenmeyer's on organic chemistry, and Bunsen's on general chemistry—truly as illustrious a band of scholars as could be found anywhere.

Under the same roof there lived Julius Bernstein (the son of the family's old friend), who was at that time one of Helmholtz's assistants, and who, as professor of physiology at Halle, has since risen to be one of Germany's great physiologists. Bernstein and the Meyers fraternized much together. To this trio there was later added a fourth—Paul du Bois Reymond, then *privat-docent* in mathematics.

Meyer's work at the University was brilliant in the extreme: he headed the lists in every course. In May, 1867, when but nineteen years old, he received the Doctor's degree *summa cum laude*—which is given on but rare occasions. Bunsen immediately appointed him to an assistantship, and here he chiefly busied himself with analyses of various spring waters by methods initiated or improved by Bunsen and his pupils.

In addition to his work at the laboratory Meyer was much in demand as a coach for the doctor's examination. Yet he found time to cultivate his artistic tastes in many ways. From his earliest days he played the violin; now he began to take lessons in piano playing. The classics he assiduously cultivated, and never missed an opportunity of attending the more notable performances at Mannheim. His week ends were usually spent wandering near Heidelberg. Julius Bernstein, who often accompanied him on these excursions, tells of a pretty little incident that occurred to them on one occasion: "Towards evening, tired and weary after a day's tramping, we entered a wine cellar, and there sat down at one of the tables. A young peasant who happened to come in came up to us and asked permission to sit at our table. As we were chatting with him he fixed his eyes on Victor, stared at him for some time, and then exclaimed, 'See here, never in my life have I seen such a handsome fellow as you are.'

Just quite in this way Victor was hardly ever addressed again, but it is a fact that the ladies were all more or less in love with him."

In the late sixties, Baeyer had already established a reputation such as to attract students from all parts of the world, and it was to Baeyer's laboratory in Berlin (at the *Gewerbeakademie*) that Meyer proceeded in 1868. And what a busy and profitable place this proved to be! Baeyer himself had already begun his classic researches on indigo blue. Graebe and Liebermann had just produced alizarin artificially—the first instance of the synthesis of a plant-coloring matter. S. Marasse, B. Jaffe, E. Ludwig, and W. A. van Dorp were all helping to make the laboratory famous.

The young Meyer made more than a favorable impression, according to Liebermann's testimony: " Meyer's remarkable ability could hardly pass unnoticed. His congenial personality added but to the esteem in which he was held. He seemed to have read everything, and his memory was simply phenomenal. . . . Many obscure references that at that time were rather difficult to locate could easily be traced by consulting Meyer. He could usually tell you not merely the volume but the very page."

During the three years that Meyer remained here he published several important papers, among which may be mentioned his contributions on the constitution of camphor, of chloral hydrate, and of the benzene ring.

Towards the end of 1870, at Baeyer's recommendation, Meyer was appointed professor extraordinary at the Stuttgart Polytechnik, of the chemical laboratory of which H. v. Fehling was the director. Here the twenty-three-year-old professor, who had never been *privat-docent*, was put in charge of the organic chemistry department.

Stuttgart proved an incentive to renewed activity. Here he announced his discovery of the nitro compounds of the aliphatic series—his first really lasting contribution to the advancement of the science.

Though little burdened with routine at Stuttgart, Meyer was sorely tempted to accept a first assistantship at the University of Strassburg, offered him by Baeyer, who was about to take charge of the chemical institute there. On the one hand, there was the opportunity of once again coming in contact with the great master

mind; on the other hand, he was to be put in charge of the analytical department, and this meant running around the laboratory and attending to the wants of the students the greater part of the day. In Stuttgart he therefore remained—till one day President Kappeler, of the Zürich Polytechnik, chanced to walk into his lecture-room. Kappeler was so impressed with the young man's ability that he immediately offered Meyer the vacant professorship of chemistry at Zürich. And so at twenty-four Victor became a full-fledged professor *ordinarius!*

This appointment Meyer celebrated in a highly appropriate way: he became engaged to the companion of his youth, Fraulein Hedwig Davidson.

The Zürich laboratory was divided into two parts, the analytical and the technical, and of the former Meyer had charge. His predecessor was Wislecenus, who had accepted a call to Leipzig. Bolley had control of the technicological side. With Bolley, as well as with Eduard Schar, the professor of pharmacy, and Ernst Schulze, the professor of agricultural chemistry, the newly-appointed instructor fraternized much. The researches that had been started at Stuttgart were now renewed with the utmost vigor. In the beginning all did not go well. A mercury compound of nitromethane which Rilliet, his private assistant, had prepared, exploded, with serious injury to Rilliet. Wurster was brought from Stuttgart to replace him, and Meyer found him a competent substitute. "I have given him rooms in the laboratory," he writes; "this is of the utmost importance, as thereby he can do twice as much work. He is very conscientious—so much so, that I think I shall send for another one of my Stuttgart pupils."

Satisfied as he was with the assistants he imported, Meyer was far from satisfied with the assistants he found, or with the cool reception accorded him by the students. In Stuttgart he was the idol of his pupils; here the men had little sympathy with one so much taken up with the theoretical aspect of the subject. "One single publication on some cheese preparation makes one far more celebrated in Switzerland than one thousand discoveries in the field of pure organic chemistry," he writes bitterly. But the day was to come when the Swiss were to venerate him, and the day was also to come when Meyer would love his Zürich students and the Zürich atmosphere.

From the very first he had his hands full. "I am very busy," he writes, "as you can conclude from the following: I devote eight hours to lectures in organic chemistry, two to lectures on analytical chemistry, two to metallurgy (in place of Kopp, who is in Vienna), and besides this I have to superintend Kopp's as well as my own laboratory." But this did not prevent him from pursuing his research work. In the month of July he records the synthesis of diphenyl-methane from benzoyl alcohol and benzene. This compound, which melts at 26° C., Meyer placed on his writing table, and used it in place of a thermometer. At ten in the morning, if the substance was in a molten state, the Herr professor would announce that weather conditions made it impracticable to pursue any work in the laboratory; and then professor and students would go bathing. On one of these occasions Meyer rescued one of his assistants, Michler, from drowning.

But recreation played but a small part in the Zürich life. Apart from the regular students there were (in 1876) twelve men working for their doctorate, in addition to Meyer's four assistants, who had already passed that stage, but who were busier than any of the candidates creating new compounds. The nitro compounds of the aliphatic series, the first piece of classical research with which the name of Meyer is associated, were engaging the attention of the youthful professor; but even at that time he made excursions into the realm of indigo chemistry (the artificial production of which he hoped to solve in one week!) and discussed Van't Hoff's views on optical activity and the asymmetry of the carbon atom.

With Baeyer, the great master, and with Graebe and Liebermann, Meyer carried on a brisk correspondence, the letters dealing chiefly with views on current scientific topics. In 1876 his elder brother obtained a position near Zürich and Victor's delight knew no bounds. Gustav Cohn, the economist, and Eduard Hitzig, the psychiatrist, were about this time appointed professors at the University. Graebe himself, who had been in delicate health, resigned from his Königsberg position and came to Zürich to join the happy crowd. But for a rather unpleasant polemic with Ladenburg (Meyer later dubbed this episode the *Ladenburg-Fieber*) which tended to undermine Meyer's delicate constitution, there was nothing at this time to mar the even tenor of the young man's life. He had just begun his second classical

work: his method of determining vapor density. We find him writing to Baeyer asking for some methyl anthracene, a substance which by analysis can hardly be differentiated from ordinary anthracene, but which can easily be identified by the vapor density method.

In the spring of 1876 Meyer received a call from the Königsberg authorities, but by this time he had come to like Zürich and was loath to leave it. As an inducement to remain, and in appreciation of his services, Kappeler had Meyer's salary increased by 1500 francs a year. Not so very long after this a vacancy occurred in Erlangen. The rumor had gone forth that Meyer would be offered the position, and this came to the ears of the president. Without waiting to hear from Meyer, Kappeler took the initiative by informing him that the wish of the governing body to have him remain in Zürich was so earnest that they were willing to make his position tenable for life, provided he would decide to stay (Meyer held it on a ten-year contract), and that they would further increase his salary by 1000 francs. "As I had no desire to go to Erlangen," Meyer writes to Baeyer, "I gave him the assurance with pleasure."

The miscarriage of one of his experiments before the student class made him hit upon what is conceded to be his most brilliant discovery—thiophene. "The analyses," he writes to Baeyer, "have shown the compound to have the formula C_4H_4S. It boils at 84° C. How should it be named? Kindly help me. I do not like such a name as thiofurfuran. . . . How about indogen? . . . or indophenin? or thiochrom, krytan, kryptophan? I would like to get hold of a name that would please you, too. Possibly the Frau Professor would like to take part in this." Thiophene was the name finally selected, and this became the mother substance of a group of compounds almost as extensive as benzene itself, which the genius of Meyer introduced into organic chemistry.

In January, 1884, in the company of Professor Bluntschli, the architect, Meyer undertook a journey through Austria-Hungary, with the view to examining the various chemical laboratories there. Their journey lay over Munich, and here the first stop was made. "We have already been in Munich and Graetz," he writes "and in both places we had a most delightful time. In Munich I spent a lovely time with Baeyer, Otto Fischer, and

König, and one delightful musical afternoon with the Heyses." (Here he refers to Heyse, the poet and novelist.) Again: "The new buildings in Vienna defy description. The Parliament, the Guildhall, the University, and the Hofburg Theatre constitute a section beside which the Place de la Concorde in Paris fades into insignificance. In addition they have the recently-constructed museums by Semper, which are the finest examples of Renaissance architecture. I witnessed a performance of the *Walküre* and the second part of *Faust*. I also saw my old flame, the actress Lucca. You can imagine how happy I was to see her again after thirteen years of absence. She is as beautiful as ever, time not seeming to have altered her."

In July, 1884, Hübner, the Göttingen professor, died. Meyer's friend Klein, who informed him of this, also told him that he was a likely candidate. The thought of having to leave Zürich was quite unbearable. What had he not accomplished during these thirteen never-to-be forgotten years! But, then, to step into the world-famed Göttingen school—that had also to be considered.

Meyer had not yet reached his thirty-sixth year. He had to regard the call to Wöhler's old establishment as the highest compliment that could be paid to him. Indeed, the compliment proved a higher one than even he expected, for he was not to be selected from a group, but none others were even to be considered.

During the last days of the year 1889 Meyer proceeded to Bonn to undergo an energetic cure: a sort of massage and electrical treatment combined. He writes: "For fourteen days I lived in the strictest incognito, going under the name of Professor Meyer, of Berlin. Since a week ago I have given this up and am now with Wallach and Kekulé daily. To see Kekulé once again and to speak to him does one's heart good. You will not consider me vain when I tell you that it was delightful to hear him say to me that he considered me the foremost among the chemists of the younger generation. Wallach is a splendid type of fellow. He visits me daily. He has no easy life of it. What a pity that he cannot go to Zürich! I suppose you have heard that Hantzsch has been nominated to succeed me. I am glad to see that both Kekulé and Wallach approve of Kappeler's choice. Wallach has completed a wonderful piece of work on the terpenes which must surely become epoch-making."

Meyer left Bonn in indifferent health and after a short stay in

Zürich proceeded to the Riviera with his parents. Here he felt himself slightly better, but not very much so. "Italy and the Riviera are very nice, but only for the one who is in a position to enjoy her beauties," he writes. "In my case, where I dare not go beyond one-half hour's distance from the house, the mountains call in vain."

In this condition Meyer proceeded to Göttingen. He was comforted to a large extent in that his excellent assistant, Sandmeyer, accompanied him for the summer semester. Sandmeyer, one of Meyer's "discoveries," is to-day known wherever chemistry flourishes. He started as a mechanic in Meyer's laboratory, but soon gave this up to devote all his time to chemistry.

Meyer left Zürich without being able to take leave of his students, but some months later he returned to attend the seventieth birthday of Kappeler. At the *Kommers*, which was given in the old man's honor, Meyer was among the speakers. Professor Goldschmidt thus describes the scene: "I see him (Meyer) even now before me as he spoke to the students at the *Kommers* in the evening. The 'Züricher Polytechnikers' have, as a rule, but little opportunity of knowing the professors outside their special faculty, and have therefore but little interest in those who are not their own teachers. As Victor Meyer's slender form appeared on the platform, and as his bright blue eyes glanced around the assembly, there broke forth a shout of welcome from all—engineers, machinists, architects, as well as from his own students, the chemists—to be ended in a whirlwind of applause at the close of a speech, sparkling and witty as ever."

Meyer's reception in Göttingen was all that could be desired. His inaugural lecture created a furore (*"es war zum Brechen voll,"* he writes), and he was well pleased with so auspicious a beginning. Besides, the other men on the staff were such as any head of a department could well be proud of. C. Polstorff, K. Buchka, R. Leuckardt, P. Jannasch, and L. Gattermann were among the regular forces. Then there was the old attendant Mahlmann, whom the students of Wöhler still remembered as a marvel in glass blowing. And, finally, Sandmeyer, Stadler, and several other Zürich men completed the list.

The scientific work inaugurated here was in the main a continuation of what had previously been started elsewhere. That wonderful thiophene, which seemed to be the starting point for

as many derivatives as benzene itself, was still a keen subject for study in his laboratory. The material along these lines accumulated to such an extent that Meyer found himself warranted in publishing a book on these sulphur compounds. Vapor density determinations—a subject which had agitated him even early in his Zürich career—were being followed up with unslackened zeal.

But Meyer was never so engrossed with his own work as not to keep abreast of the work which others in the field were doing. Thus we find him engaging in a friendly polemic with Baeyer on the latter's views as to the constitution of benzene. Stereoisomerism—a term coined by Meyer—dealing with configuration in space, a subject then in its infancy, also engaged his attention, and he early applied Van't Hoff's views to explain several perplexities, such as the configuration of hydroxylamine and isomeric oximes of unsymmetrical ketones. Here we see the Professor no less proficient in the field of speculation than in that of experimentation.

Feeling the need of a comprehensive treatise on organic chemistry, which neither the German nor any other language supplied, Meyer, in collaboration with his assistant Jacobson, started his famous text-book. To this day it has not its peer. Those who have had occasion to do any extensive work in this branch of the science know well enough how indispensable a part of their equipment this book is. Unfortunately the senior author did not live long enough to see the work in its completed form (it ultimately appeared—still incomplete—in two bulky volumes).

Much as the nature and extent of the research work adds to the renown of an institution, certain other factors tend to have no small influence. When Meyer came to Göttingen the size and equipment of the laboratories were far from what could be desired, and one of his stipulations was that this state of affairs would soon be altered. With a willingness which could result only from the esteem in which Meyer was held, the authorities appropriated a sum sufficient to build a new laboratory, and gave him complete charge of supervising its construction. Of course, this took up much time, but as this was to prove the tools of the carpenter, and realizing how much the finished product is dependent upon the quality of the tools employed, Meyer threw

himself into it with a wholeheartedness which was characteristic of everything he undertook.

Another step in the direction of increasing efficiency was the formation of the Göttingen Chemical Society. The number of research men had risen to such a height—at this time there were 105—that Meyer readily foresaw the advantage of organizing a club where these men could congregate and discuss current topics. At these meetings the students would give accounts of the progress of their latest investigations, and professors and students would engage in friendly criticism. The *esprit de corps* thus created was little short of wonderful.

The one source of great worry to Meyer as well as to his dear friends was the state of his health, which at best was but indifferent. Here in Göttingen he had formed a very intimate friendship with Ebstein, a well-known professor in the medical faculty, and, fortunately for him, Ebstein was untiring in his efforts. In 1888, when Meyer suffered a bad attack of diphtheria, only his friend's constant attention saved him. Ebstein prescribed no end of rest cures. These were well enough in themselves, but, as they so often clashed with work in the laboratory, Meyer fretted not a little. However, feeling that it was a question of life and death, he usually yielded.

It was on one of these recuperation tours that Meyer revisited his old Zürich. His reception by faculty and students left no doubt as to the way they regarded their old professor. But he had already had a proof of this shortly after he came to Göttingen. Then his Zürich scholars sent him an address which he described as "*so etwas schönes habe ich noch nicht gelesen und auch noch nicht gesehen.*"

The summer vacations were usually spent in Heligoland by the sea. Here, in company with his friends, Liebermann, Tollens, Ebstein, and occasionally Kirchoff, the weeks were passed in recuperation and interchange of views.

In the fall of 1888 his quiet life gave place to days of great agitation.

On November 11 he writes to his brother: "Confidential! Yesterday I received an official communication from the ministry offering me the professorship in Heidelberg in succession to Bunsen. They are ready to do anything I want them to do. But not a soul must know of this till next Thursday. On that day the

new chemical building will be officially opened, and were this news to leak out then, it would cause a great scandal. What shal' I do, unlucky man that I am! The greatest piece of good fortune in the world, and yet here I am—a most dissatisfied beggar." To Baeyer he writes: " I must write to you in the very first place. I am not far wrong when I surmise that you have had a great deal to do with the honor that has come to me. My debt of gratitude to you is forever on the increase. The Minister of Education writes that the Faculty and Senate have nominated me *unico loco,* and that Bunsen was particularly desirous of seeing me succeed him."

In Berlin, where negotiations were begun, Althoff, the minister, was as bent upon retaining Meyer—at least in Prussia—as the Heidelberg authorities were bent upon getting him. He held out the assurance that Meyer would be the logical successor to Hofmann in Berlin, as Helmholtz and the majority of the faculty there had declared themselves in his favor. " I brushed all this aside," writes Meyer, " and told Althoff that I hoped Hofmann would write a nice obituary notice of me in the *Berichte.*" Not even the title of *Geheimrat,* which was bestowed upon him at this time, could influence him. " On the envelope you address me as *Geheimrat,*" he writes to his brother. " That, of course doesn't matter, and yet it troubles me. I have strictly forbidden any of my assistants to apply that title to me. ' Professor ' is far more to my liking, and that they shall call me, as they have hitherto done."

Urged by Bunsen, Meyer finally decided for Heidelberg. " I am the happiest and yet the most wretched of men," he writes.

Before proceeding to asume his duties in Heidelberg he spent several delightful days in Bordighera. Here were Baeyer, Emil Fischer, Wallach, and Quincke, " the masters of them that know " in chemistry.

To Heidelberg Meyer took as his assistants Jannasch, Gattermann, Jacobson, Auwers, and Demuth. At this day when one reads these names one cannot but help admiring Meyer's wonderful judgment of men. Every one of these five has since made an enviable name for himself.

" I saw him in Heidelberg in the spring of 1891," writes Thorpe,[42] " when he was busy with the enlargement of the old laboratory, and it was with a glance of pride—a pardonable pride—that he pointed out the places where he and I had worked

with 'Papa' Bunsen. . . . It was strange, too, to hear the sound of children's voices and their laughter, and the bustle of servants in what was formerly the silent, half-deserted rooms overlooking the Wredeplatz; and stranger still to me was it, as we together called upon Bunsen, sitting solitarily in his rooms overlooking the Bunsenstrasse, to behold the meeting and to listen to the greeting of these two men—the memory of whose names and fame Heidelberg will cherish so long as Heidelberg exists."

At forty-one Meyer found himself head of—what then was—the most famous chemical school in the world. For many years Bunsen had been looked upon as the Nestor of the science. The most promising students all flocked to Heidelberg to sit at the feet of the great master. Almost every university chair of chemistry of any pretensions was filled by one of Bunsen's pupils. Yet of all of them Bunsen looked upon Meyer as the most brilliant, and it was because of that that he was so eager to have Meyer succeed him.

As in Göttingen so in Heidelberg, Meyer continued researches long before begun. These were, however, supplemented by one important addition: a study of conditions determining both the gradual and explosive combustion of gaseous mixtures, and this new phase of his labors may be regarded as the outstanding feature of his Heidelberg tenure of office.

All would have been well but for his physical sufferings. These re-commenced soon after he came to Heidelberg, and they scarcely left him till the day of his death. Early in the morning of August 8, 1897, he took his own life by swallowing some prussic acid. On the table he left this message: "*Geliebte Frau! Geliebte Kinder! Lebt wohl! Meine Nerven sind zerstört, ich kann nicht mehr.*" At the early age of forty-nine, when in the full bloom of his powers, this remarkably gifted man passed away.

. . . . . .

From the reports which have come to us it would seem that Meyer's qualities as a teacher were rivalled only by his powers as an investigator. Mention has already been made of his histrionic talents; these were put to effective use in later days as professor. His extraordinary command of language, spoken in a well-modulated voice, and coupled with a well-nigh unrivalled knowledge of his subject, went far to assure success. In addition, Meyer's laboratory technic, one of his precious assets, stood him in excellent stead when experimentally illustrating his lec-

tures—and his lectures were always copiously illustrated by experiments, in the preparation of which no pains were spared.*

Nor as a man did he fall short. Sympathetic by nature, generous almost to a fault, always eager to acknowledge the labor of others, with not a taint of jealousy in his make-up, full of a hearty optimism which made him a congenial companion, a splendid *raconteur,* an excellent after-dinner speaker, a violin-player of no mean calibre—these qualities endeared him to all. His friends, Bunsen, Kopp, Erlenmeyer, Baeyer, Graebe, Kekulé, Liebermann, Fischer, etc., respected him not only as an eminent colleague, but loved him as a man of worth.† His house was a centre not merely for scientific, but literary and artistic notables. At these gatherings his charming wife and four daughters did much to contribute towards a delightful evening.‡

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* "I well recollect that the word most frequently used in Zürich in defining the opinions of Victor Meyer's students of his lectures was 'brilliant!' (Watson Smith). "What particularly struck me about his lectures was their finished style. He made fairly constant use of notes, speaking with great rapidity. Yet his treatment of the subject was very clear, and his language perfect. The experiments were always well prepared and exceptionally successful. Indeed, his lectures were most popular. . . ." (John I. Watts.) See E. Thorpe.[42]

† *Ich muss Euch doch sagen, wie entzückt ich wider von allem bin: Berlin, Halle, München. In München war es ganz herrlich mit Baeyers, Fischers, und dem anderen. Baeyer ergriff einmal bei Tische das Glas um mit Emil Fischer und mir Schmollis zu machen, denkt nur, der liebe Mann! Es brachte uns momentan in förmliche Verlegenheit, denn natürlich brauchten wir mehrere Tage, bis wir uns daran gewöhnen konnten, ihn ungeniert Du zu nennen.*" (Victor Meyer, in a letter to his brother, October 17, 1883.)

‡ "*Die jugendliche Gestallt, der fein geschnittene, geistreiche Kopf, das seelenvolle blaue Auge, der Wohlklang der Stimme nahmen schon äusserlich Jeden für ihn ein.*" (Liebermann.[41])

"Young, handsome, well dressed—for a German professor—with a quick wit and a genial manner, he was a welcome addition to any gathering." (John I. Watts.)

"No one was more popular at these gatherings (the Chemical Society at Heidelberg) than Meyer. His nimble mind and retentive memory, his gift of ready speech, his sense of humor, and genial manner combined to make it pleasant to listen to him, no matter whether he was, in accordance with the rules of the society, called upon to give an account of some work which had just been published, or whether he was discussing and criticising a communication from a fellow-member." (Thorpe.[42])

Meyer was not one of those professors who shrink from popularizing their science. He frequently wrote for the *Naturforcher, Naturwissenschaftliche Rundschau, Deutsche Revue, Deutsche Warte.* Even in Harden's *Zukunft* we find an article on Pasteur in which the attempt is made to explain the asymmetry of the carbon atom to a lay public. Nor were his activities confined to strictly scientific subjects. In pure *belles-lettres* he published "Wanderblättern und Skizzen Aus Natur und Wissenschaft" and "Märtztage im Kanarischen Archipel."

At the time of his death Meyer was president of the German Chemical Society, Emil Fischer being the vice-president. In 1888, when the new building at Göttingen was finished, the title of Geheimrath was bestowed on him. He was also a member of the *Akademien der Wissenschaften zu Berlin, München; die Gesellschaft der Wissenschaften zu Upsala,* and *Göttinger Gelehrte Gesellschaft.* From the Royal Society of London he received the Davy Medal, and the University of Königsberg granted him the degree M.D. (Hon.).

II. HIS WORK.

Victor Meyer, together with his students, published several hundred papers during his short but very strenuous career. It becomes, of course, quite impossible to review each of these separately. However, a fair idea of the nature and extent of Meyer's work can be given without very much difficulty, for, however diversified and disconnected his writings seem when some of the titles of his papers are glanced at, in reality there is a very remarkable unity existing among them. Brushing aside his preliminary skirmishes into the constitution of chloral hydrate and that of camphor—work done primarily to familiarize himself with the research methods in organic chemistry—we see that, starting with his celebrated investigation of the nitro compounds of the aliphatic series, all his subsequent work was the expansion of a solid foundation. The action of nitrous acid on the aliphatic nitro-compounds led to the nitrolic acids; these again, with their oxim-like structure, paved the way for the study of hydroxylamine and the oximes. Attempts to establish the molecular formulæ for some of his compounds having a high boiling-point, and which could be prepared in relatively small amounts, led to his vapor density method, which in turn gave rise to an

almost endless series of pyrochemical investigations. True, in this chain of well-connected links thiophene finds no place. But then the discovery of thiophene had its source in a lecture experiment which proved a failure!

The Nitro Compounds of the Fatty Series.

A characteristic of aromatic compounds is the ease with which they form nitro bodies of the type $R . NO_2$, where nitrogen is directly attached to carbon. Prior to Victor Meyer's time but few nitro compounds of the aliphatic series were known, and these had been prepared by special methods. No general method of preparation had been devised. While still in Stuttgart, Meyer's attention was drawn to the subject, and there, after many trials, he obtained the key to the difficulty. He found that when an equivalent quantity of amyl iodide was added to dry *silver nitrite* (and the use of the silver salt here is all-important), the mixture heated for some time and then fractionally distilled, the major portion came over at 150° to 160°. Analysis showed this product to possess the formula $C_5H_{11}NO_2$. This reaction, therefore, proceeded according to the equation: $C_5H_{11}I + A_gNO_2 = A_gI + C_5H_{11}NO_2$. But this compound could have one of two formulæ: either $C_5H_{11} . ONO$ (a nitrite, where the nitrogen is combined with the oxygen, and *not* directly with carbon), or $C_5H_{11}NO_2$ (a *nitro* compound). Now the nitrite was a well-known compound which had been prepared by the action of nitrous acid on amyl alcohol, and which had a boiling-point of 96° C.—more than 55° lower than the oil obtained by Meyer. Clearly, then, we were here dealing with the other modification.[1]

This Meyer established beyond dispute in his following two publications.[2, 3] In the aromatic series a nitro compound is readily reduced to its corresponding amine ($R . NO_2 \rightarrow R . NH_2$). This was found to be just as true for these aliphatic compounds.

On the other hand, their isomers, the nitrites, when reduced, yielded alcohol and ammonia. Again, the nitrites could easily be hydrolyzed to alcohol and nitrous acid, whereas sodium hydroxide did not decompose the nitro compounds.

A systematic investigation of these nitro-paraffins was now undertaken. Meyer had originally selected the amyl compound because he feared that, ethyl nitrite being very volatile (boiling-

point 16° C.), its nitro isomer would probably prove to be so too, and hence there would be great difficulty in separating the two.* But nitro-ethane was found to boil at 113° C., and the methyl, propyl, and butyl compounds were prepared in quick succession.

A study of the properties of the nitro-paraffins revealed interesting facts. They proved to be soluble in sodium hydroxide, and were reprecipitated with acids, thereby showing them to be acidic in nature. One of their hydrogen atoms could be replaced by sodium ($C_2H_5NO_2 \rightarrow C_2H_4Na \cdot NO_2$). The halogen compounds, such as $R \cdot CHClNO_2$ and $R \cdot CHBrNO_2$, also showed acidic properties.[5, 6]

The effect of nitrous acid on nitro-paraffins was of the most surprising kind. Meyer found that when an excess of sodium nitrite was added to sodium nitro-ethane, and dilute sulphuric acid carefully poured into the mixture, a blood-red color developed: $C_2H_5NO_2 + HNO_2 = H_2O + C_2H_4N_2O_3$.[4] Meyer later obtained the same reaction by the action of hydroxylamine on dibrom-nitro-ethane: $CH_3 \cdot CBr_2NO_2 + NH_2OH = CH_3 \cdot C\begin{matrix}\diagup NO_2 \\ \diagdown N.OH\end{matrix} + 2HBr$, thereby showing these *nitrolic acids* to be nitro-oximes—a reaction which paved the way for the whole field of oxime compounds.

By the substitution of secondary nitro-paraffine $\left(\begin{matrix}R \\ R'\end{matrix}\right\rangle CH\text{-}NO_2)$ for primary compounds (RCH_2NO_2), an intense blue color was obtained: $((CH_3)_2CHNO_2 + HNO_2 = (CH_3)_2C\begin{matrix}\diagup NO_2 \\ \diagdown NO\end{matrix} + H_2O)$, giving rise to *pseudo-nitroles*.[4, 7]

Finally the tertiary nitro-paraffins $\left(\begin{matrix}R \\ R' \\ R''\end{matrix}\right\rangle CNO_2)$ did not react with nitrous acid.

Here, then, was an excellent means of differentiating between the three classes of nitro compounds.[7]

As in the nitro-paraffins, a whole homologous series of nitrolic acids and pseudo-nitroles were carefully investigated.

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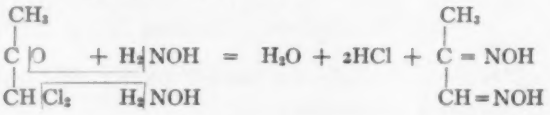
* The method with silver nitrite gives rise to both modifications, but, since the nitro-paraffins have a much higher boiling-point, their separation becomes relatively easy.

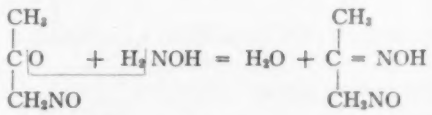
Oximes.

We have seen that the character of the nitrolic acids was elucidated by the preparation of one of their typical members from dibrom-nitro-ethane and hydroxylamine. Meyer further studied the effect of hydroxylamine on unsymmetrical dichloracetone in the expectation of getting a product similar to ethyl nitrolic acid; namely, $CH_3COCH:NOH$. But the results obtained were very different.

In his particular experiment hydroxylamine hydrochloride, dissolved in water, was mixed with an equal quantity of sodium hydroxide, and dichloracetone added. After 24 hours the product was acidified and extracted with ether. On evaporating the ether, white crystals remained. These were recrystallized from water and alcohol. Analysis showed the compound to correspond to $C_3H_6N_2O_2$. This compound, then, contained not one but *two* atoms of nitrogen—which, of course, immediately excluded the simple nitrolic form. The reaction, Meyer suggested, could be most simply explained as follows:[8]

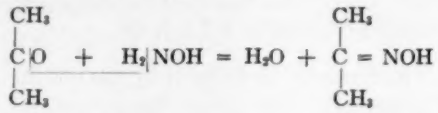


a reaction which was somewhat supported by the fact that the compound could also be obtained by treating nitrosoacetone with hydroxylamine:



Thus was the first oxime prepared. Meyer immediately turned his attention to the action of hydroxylamine on aldehydes and ketones; that is, substances containing the group $=CO$. Here he anticipated that the oxime formation would prove a general one, and his expectations were more than realized. When acetone was added to hydroxylamine hydrochloride mixed with an equivalent quantity of 10 per cent. sodium hydroxide, and the mixture allowed to stand for 24 hours, the odor of acetone disappeared. The solution was extracted with ether, and the ether evaporated, leaving white prismatic crystals. Analysis and vapor density

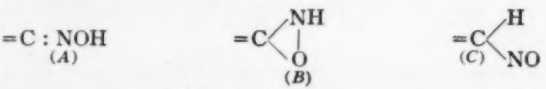
determinations gave the formula C_3H_7NO:[9]



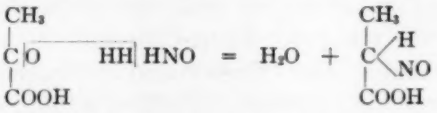
Acetaldehyde was shown to behave similarly.

The further work of Victor Meyer and his pupils showed that the reaction was quite a general one.[10]

If we now turn to the question of the constitution of these oximes we find that his work is a clear extension of his investigations into the constitution of the nitrolic acids. It was clear enough that hydroxylamine could convert the = C : O group into = CNHO, but what structure was to be assigned to this = CNHO? Three possibilities presented themselves:



In the first place, was hydroxylamine capable of giving rise to a true nitroso compound such as (*C*) ? In order to test this, Meyer prepared α-nitrosopropionic acid, $CH_3 . CH(NO) . COOH$, from methylacetoacetic ester and sodium nitrite in sodium alcoholate, and then he showed that this same compound could be obtained from pyroracemic acid with the help of hydroxylamine:[11]

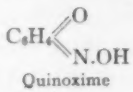


Of course, this might be taken as evidence that hydroxylamine can give rise to true nitroso compounds. However, further work—such as the failure to get nitroso compounds by the action of nitrous acid on the phenylated benzyl cyanide $(C_6H_5)_2CHCN$, which should have given $(C_6H_5)_2C(NO)CN$—tended to shift him to the viewpoint that most nitroso compounds, if not all, are, in reality, isonitroso, or oxime-like substances.[12] *

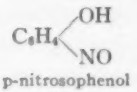
There was still the possibility that the compound had a formula such as is shown under (*B*). Meyer prepared the benzyl

* "*Die Versuche zeigen . . . die unüberwindliche Abneigung welche in der Natur gegen die Bildung wahrer Nitrosokörper besteht.*"

derivative of acetoxime, which could be represented either as $CH_3.C.CH_3$ (corresponding to (A)), or $CH_3.C.CH_3$ with $O-N.C_7H_7$ (corresponding to (B)). The former, on reduction, should have yielded benzyl alcohol and ammonia, the latter benzylamine. The products obtained showed that formula (A) was the correct one.* However, the situation was much complicated by Goldschmidt's discovery (in Meyer's laboratory) that quinone and hydroxylamine produced a compound (a) in every way identical with Baeyer's nitrosophenol, obtained by the action of nitrous acid on phenol



Quinoxime
(a)



p-nitrosophenol
(b)

(b) :[13] and to this day the question of the constitution of quinones is a debatable one.†

Of the many interesting properties brought out by a study of these oximes, mention may be made of Meyer's observation that, whereas the aldoximes with acetyl chloride yield cyanides: $CH_3 . CH : N . OH = CH_3 . CN + H_2O$, ketoximes are converted into acetyl derivatives:

$$RR'C:N.OH + CH_3COCl = RR'C:N.O.COCH_3 + HCl$$[14]

With his friend Ernst Schultze, who was at the time professor of agricultural chemistry at the Zürich Polytechnik, Meyer investigated the effect of hydroxylamine on the growth of plants.[15] The importance of nitric acid and ammonia in nitrogen assimilation was well known. Hydroxylamine, argued the authors, might be regarded as fitting with the scheme

$$HNO_3 \xrightarrow{\text{reduction}} NH_3 \xrightarrow{\text{oxidation}} NH_2OH$$

though no one had hitherto been able to show its presence in plant extracts. However, they found that in the presence of hydroxylamine plants died within five to six days—unlike nitric acid or ammonia, in the presence of either of which they thrived.

* As a matter of fact, evidence has since been deduced to show that the oximes can exist in either modifications,—that they are really tautomeric, readily changing from one to the other. See, for example, A. F. Holleman,[48] p. 329.

† See, for example, V. von Richter,[44] vol. ii, pp. 152, 167.

Yet their concluding note was not one of discouragement: "*Es sei daran erinnert dass z. B. Peptone eine giftige Wirkung ausüben, wenn man eine Lösung derselben in der Adern eines Thieres einspritz, während sie doch zugleich im Thierkörper als notwendige Zwichenprodukte bei der Verdauung entstehen.*"

Method of Determining the Vapor Density.

Early in his career Meyer, as every other organic chemist, had to make constant use of vapor density determinations in order to arrive at the correct formula of a substance. The methods then in use had important drawbacks, and it was the attempt to obviate these shortcomings that finally resulted in his now well-known vapor density apparatus.

The first paper to be published on the subject appeared in 1876,[16]—some four years after the publication of his first paper on the nitro-paraffins, and about six years before his discovery of the oximes. Meyer readily recognized the accuracy of Hofmann's method, then much in vogue, which in principle was similar to that of Gay-Lussac's; namely, measuring the volume of a weighed quantity of the substance which had been vaporized. But the fact that mercury was here used at once excluded its use for substances with boiling-points higher than that of this element. In that case Dumas's procedure, as further modified by Deville, Troost, and Bunsen—in principle, the weight of a known volume of vapor—was resorted to. But here again at least three grammes of the substance had to be at one's disposal—which in quantity was often far more than the total output of a newly-discovered product, often enough isolated under the most difficult conditions. Meyer, therefore, in devising his first modification had in mind these two important points: the amount of substance needed should be small (about 0.5 Gm.), and the method should be available for high temperatures. Wood's metal, an alloy consisting of bismuth, lead, tin, and cadmium, was finally adopted in place of mercury. The advantages of this alloy were several: it melted at 70° C., so that one could work with it almost as conveniently as with mercury; again, most organic vapors did not affect it, and any impurities could be easily removed; finally, it could be used for temperatures as high as the boiling-point of sulphur (444° C.). The vessel, filled with Wood's metal and the substance under examination, was placed in a bath of boiling

sulphur, and the volume of vapor, and from that the vapor density, determined by loss of weight:* "*An Stelle des für derartige Zwecke bisher einzig angewandten Quecksilbers eine nicht flüchtige Substanze also Sperr-flüssigkeit anzuwenden, eine kleine, genau abgewogene Probe der Substanz* (*ca* 0.05 *Gm.*) *in einem, von der nicht flüchtigen Flüssigkeit ganz erfüllten Gefässe zu verdampfen, und aus dem Gewichte der verdrängten Sperr-flüssigkeit das Volumen des Dampfes zu ermitteln.*"

The values obtained for substances of known molecular weight compared favorably with those calculated. For example, diphenyl gave a vapor density of 5.33; calculated for $C_{12}H_{10}$ = 5.23: diphenylamine gave 8.49; calculated for $(C_6H_5)_2NH$ = 8.47: methyl-anthracene, so closely resembling anthracene in properties, showed an appreciable difference in vapor density:

	Found	Calculated
Anthracene	6.24	For $C_{14}H_{10}$, 6.15
Methylanthracene	6.57	For $C_{15}H_{12}$, 6.63

Anthraquinone was tried to test the effect of Wood's metal on an oxygen-containing substance, and one capable of being reduced by zinc dust; found, 7.22; calculated for $C_{14}H_8O_2$, 7.19. Neither did halogen compounds present any difficulty; *para*-dibrombenzol—found, 8.14; calculated for $C_6H_4Br_2$, 8.15.

A year later Meyer published a modification of his method, extending it to substances of a lower boiling-point.[17] Here, instead of using sulphur vapor for heating purposes, the vapor of one of several liquids—depending upon the temperature required—was employed: water, aniline, ethyl benzoate, amyl benzoate, or diphenylamine. The apparatus here used was the one subsequently adopted in his displacement method, only in this case the volume of gas, instead of being measured, was still obtained by the difference in (loss of) weight before and after the experiment. Into a U-tube arrangement of some 35 c.c. capacity (*A*), so constituted as to be comparatively wide on one side and narrow on the other, about 0.1 Gm. of substance was introduced. This was weighed and filled with mercury. The wider end, tapering in a capillary tube, was now sealed off, the vessel again weighed, and then lowered into a narrow glass tube to which was fused a cylindrical vessel—precisely the one used to-day. Surrounding the glass

* For details see the original paper.[16]

tube was a wide glass cylinder closed at the lower end, and containing a liquid of a higher boiling-point than the substance under examination. This liquid was now heated to its boiling-point. The substance in (*A*) was, of course, vaporized, and a certain quantity of mercury was thereby forced out. After this ceased, *A* was taken out, cooled, and weighed. The vapor density could then be determined after correcting for temperature, pressure, and length of mercury column in (*A*).

His second modification, where the vapor of the examined substance displaces an equal volume of air, which is measured,[18] is so well known that no description of it need be given here.* The primary object of this modification was to make the method suitable for substances that are attacked by mercury and Wood's metal. The only data here necessary are the weight of substance, volume of displaced air, room temperature, and barometric pressure. The temperature of vaporization is not needed, since, all gases being equally influenced by temperature, the volume of the displaced air is the same at room temperature as the volume of the vapor would be at that temperature.†

The apparatus was further improved and extended in several ways.[19] The rather long and wide delivery tube connecting the main apparatus with the eudiometer was replaced by a short capillary tube, thereby obviating fluctuations in temperature and pressure. The adaptability of the method for substances boiling above 300° C. was assured by the use of a bath of molten lead. Later, in his pyrochemical investigations, where exceedingly high temperatures were often necessary, Meyer constructed his apparatus entirely of porcelain, and even of platinum, and heated it in a furnace.

Meyer's well-balanced mind and intensely honest disposition never allowed him to overestimate any of his results. This is well illustrated in one of his supplementary papers on vapor density.[20] Describing how extensively his method had supplanted others ‡ and adding, with all modesty, some of the many compli-

* Consult any text-book of organic or physical chemistry; for example, W. H. Perkin and F. S. Kipping,[45] p. 41; or J. Walker,[46] p. 201.

† "*Weder der Inhalt des Gefässes, noch die Versuchstemperatur in Betracht kommt, da ja das Dampfvolum immer in Gestalt eines ihm gleichen Luftvolumens bei Zimmertemperatur gemessen wird.*"

‡ See Beilstein,[47] p. 16.

ments which had been paid him regarding it,* he yet goes on to warn his scientific *confrères* of its shortcomings. The results obtained, he says, have usually shown themselves to be too high, and he would therefore recommend its use only where high temperatures have to be resorted to, or where metals are attacked. "*Es sollte das Luftverdrängungsverfahren eben nur da angewendet werden, wo die anderen Methoden nicht oder nur schwer benutz werden können; also bei sehr hohen Temperaturen und bei Substanzen, die Metalle angreifen.*" As a matter of fact, the method completely fulfills its function—which is, in reality, to determine whether the molecular weight of a substance is its simplest formula weight (as determined by analysis) or a multiple of this.

It is but fair to add that the laws of osmotic pressure have since taught us methods of determining molecular weights, which, in turn, threaten to supplant Victor Meyer's method.

His vapor density method led to an almost endless series of pyrochemical studies which were continued without interruption to the day of his death. At first inorganic substances, the molecular weights of which were doubtful, were investigated. Here most of the work was done in collaboration with Carl Meyer (no relative).[21] Phosphorus pentasulphide, indium chloride, cuprous chloride, arsenious oxide, and ferric chloride among others were closely studied. Then came a study of elements in the gaseous state (at yellow heat): mercury, oxygen, and chlorine. The last gave rise to much heated discussion, for at one time it tended to reopen the long-buried controversy as to the elementary nature of chlorine.

Thiophene.

Victor Meyer's fascinating piece of research, the discovery of thiophene, does not fit into his scheme of well-ordered investigations. As has been stated, its discovery may be attributed to —what seemed at the time—a faulty lecture experiment. In the preface to his book on "Die Thiophengruppe"[48] he says: "How I happened to hit on it must be attributed to an accident. In one

* "These methods (Diemar, Bunsen, Gay-Lussac, A. W. Hofmann) . . . are seldom employed at present in laboratories, because the recently published method of V. Meyer, characterized by simplicity in execution, affords sufficiently accurate results for all ordinary purposes." (Richter,[44] vol. i., p. 27.)

of the demonstrations I wished to show my students the color reaction for benzol—which depends upon the fact that benzol, or, as one must now say, coal-tar benzol (containing thiophene), when mixed with isatin and sulphuric acid, gives the deep blue indophenin reaction. I repeated this reaction before the demonstration and all went well. To my surprise, when I performed the test for the students the result was negative." His attention was immediately drawn to the source of his benzene, and the information was unearthed that whereas the benzene used for the lecture experiment was obtained from benzoic acid by distillation with alkali, that tried previous to the demonstration was a sample from coal-tar. Repeating the test with a coal-tar benzene, no difficulty was experienced in obtaining a positive reaction. On the same day Meyer convinced himself that the purest form of benzol obtained from coal-tar gave the indophenol reaction, and that by long heating or continued shaking of the hydrocarbon with sulphuric acid the blue color grew more and more faint. The sulphonate formed with sulphuric acid was dry distilled, and the distillate gave an intense indophenol reaction.

In his first paper [22] Meyer advanced three hypotheses to explain this curious behavior: (1) Mixed with benzene from coal-tar there may be a small amount of impurity present which acts similarly to zinc dust and aluminum chloride; that is, like a catalytic agent, "activating" the otherwise indifferent benzene. (2) Again, it may be that in benzene from benzoic acid there is an accompanying impurity which inhibits the reaction.* (3) Possibly the benzol from coal-tar contains two compounds, much alike in chemical and physical properties, one of which is, however, more reactive. The more reactive one, to which the isatin reaction may be due, is the first to be transformed into a sulphonic acid.

The last assumption proved correct.[23] The commercial benzene from coal-tar was found to contain about 0.5 per cent. of a substance, boiling-point 84° C., which, in its properties, showed similarities to benzene, and to which the isatin reaction was due.

Meyer first convinced himself that none of the common impurities found with benzene had any effect on the reaction. For

* Meyer, however, points out that the ordinary impurities in benzene from benzoic acid (diphenyl, benzophenone, etc.) do not seem to influence the reaction.

this purpose he successively mixed an "inactive" benzene (that is, a sample that did not give the isatin test) with toluol, xylol, naphthalene, anthracene, pyridin, quinolin, anilin, etc., but not in a single case was the test obtained. Ethyl mercaptan showed itself an exception; here the blue color appeared, but disappeared within a few minutes.

Further, benzoic acid, prepared from a Merz sample of coal-tar benzol by sulphonation and distillation with potassium cyanide, when distilled with sodium hydroxide, yielded a benzol which gave a positive isatin reaction.

Meyer prepared the new substance from ten litres of benzol by the sulphonation method. From the sulphonic acid a few cubic centimetres of liquid, boiling at 85° C., which did not solidify on cooling with a mixture of ice and salt, and which contained appreciable quantities of *sulphur,* was obtained. This liquid gave an intense isatin reaction—so much so, that it had first to be diluted with "inactive" benzol or ligroin before the isatin and sulphuric acid could be added.

It was clear now that the reaction was due to some substance *in* the benzol.

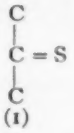
Now, argued Meyer, since this new substance contains sulphur, indophenin itself—the result of the reaction of isatin and sulphuric acid on coal-tar benzol—probably contains this element also. And indeed he showed that the purest samples of indophenin and bromindophenin, with which his friend Baeyer supplied him, contained sulphur.

Through the kindness of R. Bindschendler the facilities of the dye factory of Bindschendler, Busch & Co. were placed at Meyer's disposal. He was thereby enabled to prepare the new compound in appreciable quantities. Two hundred and fifty litres of the purest commercial benzol were shaken for four hours with 25 litres of concentrated sulphuric acid. The resulting sulphonic acid, when converted into its lead salt, yielded 16 kilogrammes. This lead salt consisted mainly of the salt of the new sulphonic acid, mixed with a little lead benzene sulphonate. This was decomposed with hydrogen sulphide, filtered from lead sulphide, and the filtrate submitted to dry distillation. Later, adopting Caro's modification, the process was considerably improved by distilling the lead salt with one-quarter its weight of ammonium chloride. The raw distillate was purified by shaking first with water, and then with concentrated sodium hydroxide,

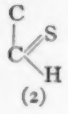
and finally freed from water with calcium chloride. This was again distilled. The oil so obtained, when further freed from water by means of calcium chloride, showed itself to be a mixture of about 70 per cent. of the new substance and about 30 per cent. benzol. For further purification, 20 c.c. samples of raw thiophene were diluted with 2 litres of ligroin and shaken with 200 c.c. concentrated sulphuric acid until the ligroin layer no longer gave an isatin reaction (this required from one to two hours). The thiophene sulphonate was separated from the ligroin, diluted with water, and lead carbonate added. The lead salt was next decomposed with hydrogen sulphide, filtered, and the filtrate, consisting of thiophene sulphonic acid, quite free from benzol derivatives, was dry distilled. The thiophene so obtained was washed with potassium hydroxide, dried by means of calcium chloride, and once again distilled. The liquid boiled at 84° C., and analysis and vapor density determinations showed it to have the formula C_4H_4S.

The following year Victor Meyer considerably improved the method of preparation.[24] He found that by the use of a limited quantity of sulphuric acid the thiophene could be extracted direct from coal-tar benzene without the accompaniment of any benzol. Two thousand kilogrammes of pure coal-tar benzol were shaken with 100 kilogrammes of concentrated sulphuric acid for six hours. The resulting sulphonic acid was converted into the corresponding lead salt, and this distilled with ammonium chloride, yielding chemically pure thiophene. For every kilogramme of the lead salt 135 grammes of thiophene were obtained. The sulphur calculated for $C_4H_4S = 38.1$ per cent.; as actually found = 37.9 per cent.

With regard to the constitution of the new compound, Meyer, in this early paper of his, advanced three possibilities as to the part played by the sulphur in the configuration of the molecule:



(1)

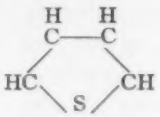


(2)

(3)

The first, a thioacetone, would have had a tendency to coalesce into two molecules; the second, a thioaldehyde, was immediately dismissed by Meyer as not in any way agreeing with the known properties of the substance; the third seemed most

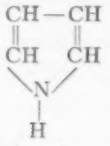
probable. In that case the configuration, thought Meyer, might be of some such nature as this:



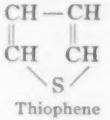
And this later investigation fully confirmed.[25] The name finally adopted for the new compound was "thiophen"—"thio" because of its sulphur content, and "phen" as showing its similarity to the phenyl group. Well was Meyer justified in writing that "*ihre (der Thiophen) grosse Aenlichkeit mit der correspondierenden Derivaten des Benzols . . . scheint sich ein weites Gebiet zu öffnen, dessen Bearbeitung eine Ausbeute an interresanten Körpern in Aussicht stellt: an Körpern, deren Eigenschaften denen der analogen Abkömmlinge des Benzols gleichen, und auch eine ähnliche Constitution besitzten, nur das sie, statt von Benzol, von einem schwefelhaltigem Stammkorper mit 4 Atomen Kohlenstoff deriviren.*" [23]

The similarity between thiophene and benzol was strikingly shown by the preparation of the homologues of thiophene * and its derivatives, such as tetrabrom thiophene, C_4Br_4S; thiophen-sulphonic acid, $C_4H_3S-SO_3H$; thiophensulphochloride, $C_4H_3S-SO_2-Cl$; thiophensulphamide, $C_4H_3S-SO_2-NH_2$; thiophennitril, C_4H_3S-CN; thiophencarboxylic acid, $C_4H_3S-COOH$;[26] nitro-compounds;[27] condensation products by the use of Baeyer's and Friedel-Craft's reactions,[28] etc.

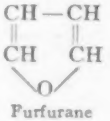
Further, Meyer showed that pyrrol, like thiophene, reacts with isatin and sulphuric acid, and the latter is the mother substance of an almost innumerable series of dyes closely related to those obtained from pyrrol. This, and the evidently close relationship between furfurane and thiophene



Pyrrol



Thiophene



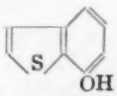
Furfurane

* The methods used for preparing the homologues of thiophene are in every way analogous to those used in the preparation of the corresponding benzol homologues.

seemed to justify the conclusion that of the three acetylene groups in benzene, *one* can be replaced either by S, O, or NH, without materially altering the character of the benzene (*"ohne dass dadurch der eigenthümliche Charakter des Benzols und seiner Abkömmlinge aufgehoben wird"* [29]).

Methods of producing thiophene otherwise than from benzene were developed by Meyer. Thus he found that it could be obtained—in small quantities, to be sure—by passing acetylene or ethylene over boiling sulphur; [30] by passing ethyl sulphide through tubes heated to redness; by bringing ethylene or illuminating gas over heated pyrite; by heating crotonic, butyric (*not* isobutyric), or valerianic acid, or paraldehyde with phosphorus trisulphide.[31]

What held true for benzol Meyer found to be true for toluol, xylol, etc. Thus he found that Laubenheimer's reaction for anthraquinone—where toluol, drop by drop, is added to a dilute aqueous solution of anthraquinone, then, under cooling, sulphuric acid, and, after a few minutes, some water is added; the mixture, when treated with ether, gives a beautiful violet-red—is not given if the toluol used be *pure*. By merely shaking the toluol for some time with concentrated sulphuric acid Laubenheimer's test proved negative. Further, coal-tar toluol was shown to contain sulphur, whereas toluol, first treated with sulphuric acid, did not. This led Meyer to conclude that in coal-tar, side by side with the benzene hydrocarbons, there are a whole series of corresponding thiophene derivatives,[32] which, indeed, was shown to be the case.[29, 33, 34] Toluol (methyl benzol), for example, was found to contain thiotolene (methyl thiophene)—(see also Richter,[44] **2**, 453). And the many possibilities of extending the whole subject were still further revealed when by the use of Fittig's condensation a thiophene of the naphthalene series was obtained: thiophene-aldehyde and succinic acid were condensed, giving the α-naphthol of the thiophene series:[35]



Like all his other researches, his thiophene work reveals the man with the true scientific trend—the method of logically developing a subject. The first slow method of extracting thiophene from coal-tar was followed by improved methods; then came the recog-

nition of its close constitutional similarity to benzol, and further to furfurane and pyrrol; and from here on to an endless series of homologues, substitution products, isomers—with their properties closely allied to the corresponding benzene derivatives.

. . . . . .

This is far from an exhaustive account of Meyer's activities. Little more than the *leit-motivs* in his researches could be touched on. And much of his work—especially that pursued during his last years in Heidelberg—has not been touched on at all; for example, his studies concerning the slow combustion of gas mixtures,[36] the dissociation of hydrogen iodide,[37] the iodo, iodoso, and iodonium compounds —where iodine functions as does nitrogen in ammonium substances,[38] steric hindrance * [39]—to mention but a few.

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* "*Sobald in einer substituierten Benzoesäure die beiden, den Carboxyl benachbarten Wasserstoffatome durch Radikale, wie Br, NO_2, NH_2, CH_3, unsw. ersetzt sind, resultiert eine Säure, welche durch alcohol und Salzsäure nicht, oder nur sehr unvollständig verestert wird.*"

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Electrolytic Chlorine for Laundries. H. P. HILL. (*Electrical World,* vol. 68, No. 5, July 29, 1916.)—For several years a number of the larger laundries have prepared their own bleaching material by the electrolysis of salt solution, finding it cheaper to produce their own "bleach" than to purchase the bleaching compounds which are largely manufactured abroad and exported to this country. In recent months, however, the sharp advance in prices of bleaching compounds of all kinds has made it increasingly desirable for even smaller laundries to produce their own chlorine solution by the electrolysis of salt and water. The electrolytic load thus afforded the central station is comparatively long-hour in character, and may be arranged so as to fall entirely during the daylight hours.

A 50-gallon outfit requires 25 ampères of direct current at 110 volts. The equipment comprises a 50-gallon wood tub mounted on a stand three feet above the floor and filled with a solution of common salt and water. The tub is provided with a revolving paddle to agitate and dissolve the salt. Alongside of the tub is mounted a soapstone box containing the electrodes. The salt water from the tub is admitted to the negative element and is discharged at the positive element. From the discharge the chlorine solution flows into a tub on the floor, from which it is dipped and used in the washing machine.

NOTES FROM THE U. S. BUREAU OF STANDARDS.*

THE INTERNATIONAL SYSTEM OF ELECTRIC AND MAGNETIC UNITS.†

By J. H. Dellinger.

Two electric units, the international ohm and ampère, have been defined in terms of definite standards by international congresses. These standards are maintained by the national standardizing laboratories, and are the basis of all electrical measurements. The units of the various electric and magnetic quantities are derived in practice from these fundamental units by the ordinary equations of electrical theory. Thus a complete and distinct system of electric and magnetic units is in use, based on the international ohm and ampère, the centimetre, and the second. While these international units differ in their derivation from the electrostatic and electromagnetic units, they nevertheless represent very closely the theoretical electromagnetic units. The very slight differences in magnitude between the international and the corresponding electromagnetic units are determined by absolute measurements made from time to time. The electromagnetic units are of much less practical interest than the international units.

One of the reasons why the international system is the most convenient and the most used electrical system is because it is centred around the phenomena of electric current. Electric current is more familiar and of vastly greater practical importance than electrostatic charges or magnetic poles, upon which the other two familiar systems are based. In the international system the magnetic pole is given a subordinate position. Since a free magnetic pole does not exist in Nature and magnetic pole strength does not appear in engineering formulæ, its prominence in the electromagnetic system has not been an advantage of that system. Another fortunate aspect of the international system is the con-

* Communicated by the Director.

† Scientific Paper No. 292.

venience of its dimensional expressions. They are very simple, and directly suggest the ordinary relations of electrical theory and practice. They are, in fact, as helpful in electricity as the usual dimensional expressions in length, mass, and time are in the domain of mechanics. The international electrical system is valuable only in electricity and magnetism, having no utility in mechanics or other parts of physics. It gives dimensions as awkward for the quantities of mechanics as the electromagnetic system gives for electrical quantities, and is, therefore, not of such general application as the systems in which length, mass, and time are fundamental.

The international system furnishes no justification for the use of the word "gauss" as the name for both the unit of induction and the unit of magnetizing force. This double usage is an inconvenience in practice.

New systems of electric and magnetic units have been proposed from time to time, and some of these are now used to a limited extent in certain books and publications. They all involve the definition of new units of certain quantities in such a way as to redistribute the factor 4π in the equations. An attempt to redistribute the 4π's in an advantageous manner has been called "rationalization" in the literature of the subject. A careful study has been made to determine whether the advantages of these proposed systems are such as to justify the trouble and confusion incident to a general change of units. No such advantage has been found. Of course, no system eliminates the 4π entirely. All of the proposals except Heaviside's involve changing the unit of permeability by a multiple of 4π. While Heaviside's system leaves permeability unchanged, it makes a drastic change in practically every other unit.

A strong reason against a general change of units for the purpose of rationalization is the fact that a rationalized system is obtained merely by using the ampère-turn as the unit of magneto-motive force. Upon writing the equations necessary to make this widely used unit fit in with the other units, the system is found to be as good as, or actually superior to, the various proposed systems in every respect. It is interesting that the units which have undergone the evolution of actual use are not wanting in academic appropriateness.

THE DENSITY AND THERMAL EXPANSION OF AMERICAN PETROLEUM OILS.*

By H. W. Bearce and E. L. Peffer.

[ABSTRACT]

THIS paper gives an account of the experimental works on which are based the expansion tables of Circular No. 57, "United States Standard Tables for Petroleum Oils." It gives a detailed description of the methods and apparatus employed in the determination of the density and thermal expansion of petroleum oils from the various oil fields of the United States.

The paper will be of interest to oil producers and refiners throughout the country.

A VARIABLE SELF AND MUTUAL INDUCTOR.†

By H. B. Brooks and F. C. Weaver.

[ABSTRACT]

THIS paper outlines the development of a new form of instrument for varying the self-inductance of a circuit, or the mutual inductance between two circuits. It consists of two pairs of fixed coils held in stationary hard-rubber disks, between which a third disk carrying two coils is arranged to be rotated. The form and the spacing of the coils were determined so as to secure the following advantages: (1) high ratio of inductance to resistance; (2) scale divisions of uniform length reading directly in units of inductance; (3) astatic arrangement of the coils, which reduces the liability of errors caused by the proximity of other instruments or of conductors carrying currents. Diagrams and data are given from which instruments of this type can be designed for given uses. Comparison is made of the new instrument and of some other older forms of variable inductor, including the Ayrton-Perry.

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* Technologic Paper No. 77.

† Scientific Paper No. 290.

PROPERTIES OF THE CALCIUM SILICATES AND CALCIUM ALUMINATES OCCURRING IN PORTLAND CEMENT.*

By P. H. Bates and A. A. Klein.

[ABSTRACT]

WITH the settlement of the question of what are the constituents of Portland cement, the next important one is, What part does each of these play in developing the physical properties of the cement? The present investigation was undertaken to study these phases of the subject.

One of the first difficulties encountered was that of producing the three constituents present in Portland cement of normal composition and burning (tricalcium silicate, $3CaO.SiO_2$, dicalcium silicate, $2CaO.SiO_2$, and tricalcium aluminate, $3CaO.Al_2O_3$) in sufficient amounts to allow of determining the rate of setting the rate of hydrating, both chemically and microscopically, and the rate of gaining strength, both as a neat and 1 : 3 standard sand mortar test-piece. A preliminary investigation of a number of commonly used "mineralizers" ("mineral catalyzers") showed that either in the presence of small amounts of boracic acid or chromium oxide both of the silicates could be produced, although to produce the tricalcium silicates six successive burnings were required. As the aluminate is not stable at its melting-point, it was made by heating it for some time below this point, and was secured without the use of any "mineralizer."

Some burnings were also made of raw materials of the composition of the silicates, to which about one per cent. alumina was added. Products resulted which it was thought would be of considerable value when determining the effects of alumina upon the properties of the silicates. Also, some burnings were made to which alumina had been added to the raw mixes in such amounts that in one burn approximately 19 parts of tricalcium aluminate would be present in the burned material with 81 parts tricalcium silicate; in another the same amount of aluminate would be present with 81 parts of dicalcium silicate, and in a third the same amount of aluminate would be present with 81 parts of equal amounts of each silicate. It was not expected that the silica would combine

* Technologic Paper No. 78.

in either burn according to the calculations, but that there would tend to be more of the tricalcium silicate in the low silica mix and more of the dicalcium silicate in the low lime mix. It was also thought that valuable results would be obtained from these burns when compared with mixes of a similar composition formed by grinding together the compounds burned separately.

The physical tests usually carried out with Portland cement were made with each of the burns, and also with cements prepared as follows: By grinding together each silicate (using separately the one prepared with the boracic acid and the one prepared with chromium oxide) with three per cent. of plaster; also, 81 parts of each silicate with 19 parts of aluminate, and, also, adding three per cent. plaster to this mixture; also, adding three per cent. plaster to a mixture of equal parts of the two silicates; also, grinding together 81 parts of a mixture of equal parts of each silicate with 19 parts of aluminate, and by adding three per cent. plaster to this. In addition to the usual tests, the amount of hydration was determined in one neat test-piece at each period broken by determining the percentage of water of hydration; microscopical examinations were also made of these test-pieces to determine the degree and character of hydration.

The results show that the aluminate sets and hydrates so very rapidly that it is almost impossible to make test-pieces. This is accompanied by a great evolution of heat. It never attains a tensile strength much beyond 100 pounds per square inch. When mixed with the silicate it affects the latter more markedly in the time of set than in the strength, tending to hasten the former and slightly reduce the latter.

The dicalcium silicate sets so slowly that the obtaining of test-pieces is difficult, on account of breaking them at the early periods by handling. At the end of one year it has a tensile strength of about 600 pounds per square inch and 5.5 per cent. water of hydration. At seven days test-pieces made of it have to be handled with extreme care and are easily crumbled in the hand; at fourteen days test-pieces broke at about 60 pounds per square inch. Mixed with three per cent. plaster, it acquires a little more strength; mixed with 19 parts aluminate, its strength is also improved somewhat. Mixed with equal parts tricalcium silicate, it reduces the early strength of the latter, but at late periods gives a very desirable cement.

The tricalcium silicate has all the properties of Portland cement; especially does it resemble the latter in the matter of set and strength. The addition of aluminate to it has a tendency to reduce the early strengths; plaster and aluminate increase the early strengths, but reduce the later ones. The mixture with dicalcium silicate, with or without plaster, gives low early strengths but increases consistently with age. The addition of aluminate, and aluminate with plaster, to the mixture of the two silicates increases the strength of the mixture at the early periods, but is not advantageous for later strengths.

A comparison of cements produced by grinding together the compounds, with those of similar composition made by burning, shows a marked similarity between the two and would almost lead to the conclusion that it would be possible to reproduce any cement, knowing the amount of each constituent, by grinding together the constituents after their separate burning.

The function of alumina in finished cement is a matter of some question. Cements can be produced satisfactorily, both in respect to time of set and strength, when it is present in amounts less than one per cent. Such cements can be manufactured only at high temperatures and with longer time of heating than is now used. It is therefore a necessity from the manufacturing standpoint, acting as a flux and reducing both the time and degree of burning.

The character of the hydration of the two silicates is such that a preponderance of either in a cement would seem to be undesirable. The dicalcium silicate, even at the end of a year's hydration, shows a very granular, sandy, porous mass; the tricalcium silicate at the end of a week is very dense, with a semi-vitreous lustre. The porous formation of the former affords too ready egress of solutions which may crystallize out and cause disintegration, or cause loss of strength through chemical reaction of the silicate with solutions; the dense structure of the latter, being due largely to the gelatinous or colloidal products of the hydration, is poorly adapted to withstand moisture or temperature changes, to the former of which colloids are extremely susceptible.

The actual products of the hydration of the two silicates and the aluminate are, with one exception, as noted by Klein and Phillips,* as follows: In the case of the aluminate, the immediate

* "Hydration of Portland Cement," Klein and Phillips, Tech. Paper No. 43, Bureau of Standards.

hydration is the formation of a gelatinous form of hydrated tricalcium aluminate ($3CaO.Al_2O_3 + H_2O$); this changes, in the course of time, to a crystalline form of the same compound; the water of hydration is loosely combined, part being lost in dry air. In the same case of the tricalcium silicate, the hydration results in the formation of a colloidal hydrated silicate and hydrated lime which is largely crystalline, though the crystals are usually poorly formed and are well scattered through the dense mass of colloidal silicate. In the case of the dicalcium silicate, the hydration results in the formation of a colloidal hydrated silicate and crystalline lime hydrate; this latter is very well crystallized and, on account of the porous nature of the hydrated silicate, occurs in large crystals. The presence of these hydrate crystals was not noted by Klein and Phillips, and they occur only when the cement is gauged with small amounts of water.

A SYSTEM OF REMOTE CONTROL FOR AN ELECTRIC TESTING LABORATORY.*

By P. G. Agnew, W. H. Stannard, and J. L. Fearing.

[ABSTRACT]

THE system was developed primarily for use in testing electrical measuring instruments. Small multiple lever controllers may be operated in any one of several laboratory rooms to give complete control of the output of a group of motor-generator sets. For example, in testing a wattmeter, or an alternating-current watthour meter on low power factor, the five levers of a controller give both a coarse and a fine adjustment of frequency, current, voltage, power factor, and an auxiliary direct-current voltage, respectively.

The field rheostats are very long, slide-wire resistances. They are tubular in form, and are wound helically with the resistance wire. They are 32 mm. in outside diameter, and as much as 12 metres in length. When necessary, they are cooled by circulating water through the tube. Special laminated brushes which bear directly on the winding are operated by small, worm-geared

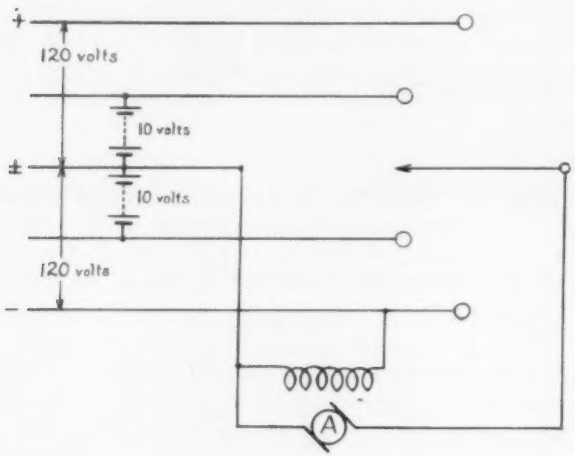
* Scientific Paper No. 291.

motors which pull them along the tubes by means of cord and pulley.

The coarse adjustment is obtained by operating the motors at normal speed, while for the fine adjustment the armatures are connected to a low-voltage battery, giving a very much lower speed. Fig. 1 shows how the 2-direction, 2-speed control is obtained with a single contact lever, by the use of a modified 5-wire system of power distribution for the operation of the motors.

Settings can be made to 0.02 per cent. in nearly every case.

FIG. 1.



Two methods of phase control are used. In one, two similar generators are on the same shaft, and the stator armature of one generator is shifted by a motor-operated worm drive. In the other method a worm drive operates the rotor of a phase-shifting transformer.

A large, motor-operated, low-voltage rheostat for currents up to 10,000 or 12,000 ampères is included in the system. Laminated brushes bear directly on water-cooled resistance tubes.

NOTES FROM THE RESEARCH LABORATORY, GENERAL ELECTRIC COMPANY.*

PHOTOMETRIC METHODS IN CONNECTION WITH MAGIC-LANTERN AND MOVING-PICTURE OUTFITS AND A SIMPLE METHOD OF STUDYING THE INTRINSIC BRILLIANCY OF PROJECTION SOURCES.†

By J. A. Orange.

THIS article gives the practical details of the apparatus required and manipulation for the purposes indicated in the title.

THE HIGH-FREQUENCY SPECTRUM OF TUNGSTEN.

By Albert W. Hull and Marion Rice.‡

THE spectrum of tungsten at voltages up to 150,000 has been studied and photographs are given showing the first, second, and third order reflections of the Kα and Kβ lines. The position of the K lines in relation to the general radiation at various voltages has been studied by means of the ionization chamber and is shown on curves of intensity for seven voltages between 40,000 and 103,000. The lines first appear at 80,000 volts, increasing in intensity with rising voltage. Kossel's quantum relations between the frequencies of K and L lines hold true for the tungsten lines. All the lines, including tungsten, can be expressed by the empirical formulæ:

$$\gamma\alpha = 1.64 \times 10^{15} N^{2.10} \text{ for the } \alpha \text{ lines,}$$
$$\gamma\beta = 1.56 \times 10^{15} N^{2.15} \text{ for the } \beta \text{ lines,}$$

where γ is the frequency and N the atomic number.

The shortest wave-length observed was 0.08 A. U. The proportionality between frequency and voltage observed by Duane and Hunt holds accurately up to 100,000 volts and less accurate measurements indicate its constancy up to 150,000 volts.

* Communicated by the Director.

† *General Electric Review*, **19** 404–5, May, 1916.

‡ *Proc. Nat'l Academy of Sciences*, **2** 265–70, May 15, 1916.

THE DISSOCIATION OF HYDROGEN INTO ATOMS. III.—THE MECHANISM OF THE REACTION.

By Irving Langmuir.*

A NEW theory of heterogeneous reactions avoiding certain assumptions of the earlier one, which experiment has recently proved untenable, is advanced. The earlier hypothesis considered that the surface of a tungsten wire in contact with hydrogen contained atoms and molecules of the gas in chemical equilibrium with each other, the two forms escaping at rates respectively proportional to their concentrations in the wire, and being absorbed at rates proportional to the corresponding pressures in the gaseous phase. The equation for heat loss from the wire thereby deduced agreed extremely well with experimental results over a range from 0.01 to 760 mm. pressure and 1000 to 3500 ° K. temperature. But the velocity of the reaction by which hydrogen in contact with a hot tungsten wire is dissociated is so enormous as to preclude the possibility of the existence of the gas as a solid solution in the metal with the attendant necessarily low rate of diffusion. Moreover, experiment has shown that, while 68 per cent. of all hydrogen molecules striking the filament at high temperatures reach chemical equilibrium before leaving it, at lower temperatures, up to 1500° K., only 19 per cent. reach thermal equilibrium, a fact for which the earlier theory offers no explanation. Work in gases at low pressures has demonstrated that electron emission is dependent upon the composition of the surface layer of atoms, and that reaction between gas and solid is also dependent upon the composition or structure of the same. It has become necessary, therefore, to assume that reaction occurs directly on the surface of the metal and involves no diffusion through even a single layer of atoms.

The new theory involves the view that on the surface of the metal the forces which hold its atoms together tend to be chemically unsaturated, and atoms or molecules of gases may be firmly held by them. In general accordance with the law of multiple combining proportions, each metal atom of the surface will be capable of holding a definite integral number of atoms of gas, or perhaps two metal atoms may hold one gas atom. Atoms or molecules so held are a part of the solid body, a real continuation of the space

* *Journal of the American Chemical Society*, **38**, 1145–56, June, 1916.

lattice of the solid, and may be said to be adsorbed. The surface of the metal is thus looked upon as a sort of checkerboard of a definite number per square centimetre of elementary spaces, each capable of holding an atom or a definite part of a molecule of adsorbed gas.

Application of this theory to the dissociation of hydrogen leads to equations identical with that derived by the older theory, which had previously (Parts I and II) been shown to be in complete accord with experimental results.

All the hypotheses considered lead to the conclusion that only a small fraction of the surface is covered with hydrogen, and that phenomena within the metal do not affect the reaction. This conclusion is confirmed by the difference in the accommodation coefficient of hydrogen in contact with tungsten at low and high temperatures, which is now easily explained by supposing the surface of the metal to be largely covered by adsorbed hydrogen at the lower temperatures and practically bare at the higher temperatures. The 19 per cent. may then correspond to the fraction of molecules condensing when they strike a surface already covered and 68 per cent. when they strike a bare surface. That the surface of tungsten is practically bare at the higher temperatures is strongly influenced by the fact that the electron emission is not perceptibly influenced by the presence of pure hydrogen.

A HIGH VACUUM MERCURY VAPOR PUMP OF EXTREME SPEED.

By Irving Langmuir.*

A NEW high vacuum mercury vapor pump, called the diffusion pump, has been devised, and its operation is explained and illustrated by a diagram. It has the advantages of extremely high speed of exhaustion, constant at all pressures, and absence of lower limit to which pressure may be reduced. The maximum speeds of exhaustion so far obtained have been 4000 c.c. per second for air and 7000 c.c. per second for hydrogen at pressures below 10 bars. Theoretical considerations indicate that this speed should remain constant down to the very lowest pressures. Further advantages are reliability and simplicity, in which respects the pump has been much improved by modifications in form and material, which will be described in later papers.

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* *Physical Review*, **8**, 48–51, July 19, 1916.

Lamp-filament Breaker. ANON. (*Electrical World*, vol. 68, No. 5, July 29, 1916).—A device for breaking the filaments of incandescent lamps which are turned into its supply department has been constructed by the Boston Edison Company, and is in regular use in the local lamp division. Among the thousands of incandescent lamps returned as having been burned out by customers are many which, though not entirely useless, are nevertheless unfit for further service. To prevent purchasers from sorting the units and reselling these with filaments intact, a means of breaking the filaments of lamps of sizes up to 250-watt tungsten was sought. As a result, an apparatus was constructed consisting of a laminated U-shaped electromagnet with a gap sufficiently wide to admit a large-sized unit between its jaws. The winding, in series with the resistance, is supplied from a 110-volt direct-current circuit. A powerful electromagnet is thus formed, whose field is produced by 7600 ampère-turns. A quick-acting lamp socket is arranged between the jaws of the U and is supplied, in series with a resistance, from a 220-volt alternating-current circuit. In addition to this fixed resistance, another can be switched-in in multiple.

As a lamp is pushed into the socket the effect is to break the filament instantly. The resistance in series with the lamp prevents short-circuiting on the 220-volt main in case of an occasional defective base. If, as sometimes happens with very large tungstens, the filament breaks and welds near the leading-in wires, the second resistance is thrown in with the lamp, thus allowing more current to flow and invariably breaking the filament. The direct-current field is left on continuously while operating. With this apparatus filaments are broken as rapidly as the lamps are inserted in the socket and placed to one side, and the lamp is in no way injured, nor is the blackening of the bulb increased.

Air Blast Alternating-current Rectifier. ANON. (*Electrical World*, vol. 68, No. 3, July 15, 1916.)—A very simple and ingenious method of rectifying high-tension alternating currents by means of an air blast has been assigned to the International Precipitation Company of Los Angeles, Calif., under United States patent 1,188,597. Wolcalt and Rieber propose to surround a rod electrode, spaced from a coöperating disk electrode, with an air blast at a pressure of about 10 pounds to the square inch. By directing the air blast along the path of the discharge, the inventors maintain that an alternating current of as much as 50,000 volts can be wholly rectified. It is also found, the inventors state, that by regulating the air-pressure it is possible to secure any desired amount of rectification. It also becomes possible to rectify both halves of an alternating-current wave and obviate entirely all expensive equipment of vacuum tubes etc.

NOTES FROM NELA RESEARCH LABORATORY.*

THE TUNGSTEN ARC UNDER PRESSURE.

By George P. Luckey.

THE following experiment was undertaken primarily for the purpose of determining whether the temperature of melting tungsten showed a marked change under pressure. For this purpose a tungsten arc was used, and the melting-point of tungsten in an atmosphere of nitrogen was determined for pressures up to 35 atmospheres. The red black-body temperatures of the melting tungsten for $\lambda = 0.661\ \mu$ were measured by means of a Holborn-Kurlbaum pyrometer of the type in general use in this laboratory. The values used for the absorption coefficient of tungsten in computing the true temperature were obtained by extrapolating from values obtained by Worthing for temperatures up to 3200° K.

The results of the melting-point determinations are given in Table I. The melting-point apparently decreases as the pressure is increased, but it is open to doubt whether this observed change is due to an actual decrease in the temperature of the tungsten, or whether the apparent diminution in brightness might not be due to an increased absorption of the gases above the surface of the tungsten. Above 12 atmospheres rather large uncertainties in the determination of the melting-point were introduced by the distortion of the image due to the refraction of the heated gases in the neighborhood of the arc.

The value of the melting-point found for atmospheric pressure agrees closely with that found by Worthing in the tungsten arc, 3630° K., while it is about eighty degrees higher than the value determined by Langmuir, 3540° K. This discrepancy is due to the different value of the emissivity of tungsten taken in the two cases. The value used by Langmuir was 0.425 at 0.667 μ, and that found from the extrapolation of the values obtained by Worthing was 0.393 at 0.661 μ. The red black-body temperatures obtained give good agreement in all cases. The value found

* Communicated by the Director.

by Langmuir was 3124° K. for 0.667 μ, while that found by Worthing was 3140° K. for 0.666 μ.

At the point where the main arc discharge centres on the electrodes of the arc, a temperature much higher than that of the surrounding melted tungsten was noticed. The temperature of this area varied with the pressure, the current through the arc, and the area over which the discharge took place. Measurements of the highest attainable red black-body temperature for 0.661 μ were made of this area at different pressures, and the values found are given in Table II. If it be assumed that the relationship found by Worthing between the absorption coefficient and the temperature of tungsten holds up to the temperatures here attained, then the values of the true temperature would be given in the last column of Table II. There is a question as to what this temperature represents. It is doubtful whether it can be assumed to be the boiling-point of tungsten. It is more probable that it represents some temperature lying between the melting- and boiling-points.

In connection with the temperature determinations, measurements were also made of the electrical characteristics of the tungsten arc in nitrogen under pressures from one to thirty atmospheres. The drop in potential across the arc, other conditions being the same, increased with the pressure, an effect similar to that observed by Duncan Rowland and Todd on the carbon arc under pressures up to ten atmospheres. At high pressures the voltage dropped as the current was increased until values of current of about five ampères were reached, after which the voltage rose with increasing current. This latter effect was probably due to the tendency of the arc to flare out to one side with larger currents, as well as to the increase of pressure in the tank caused by the heating of the gas.

TABLE I.

Apparent Melting-point of Tungsten Under Pressure.

Pressure, atmospheres	Red black-body temperature, $\lambda = 0.661\mu$	True temperature
1	3138° K.	3623° K.
4	3129° K.	3611° K.
8	3116° K.	3594° K.
11	3113° K.	3590° K.
14	3107° K.	3582° K.
18	3099° K.	3572° K.
21	3092° K.	3562° K.
28	3093° K.	3564° K.

TABLE II.

Highest Attainable Temperatures.

Pressure, atmospheres	Red black-body temperature, $\lambda=0.661\mu$	Assumed absorption coefficient	Computed true temperature
1	3559° K.	0.374	4235° K.
8	3794° K.	0.363	4602° K.
15	3907° K.	0.358	4782° K.
22	3982° K.	0.354	4912° K.
29	4022° K.	0.352	4978° K.
33	4086° K.	0.349	5084° K.

Nela Research Laboratory,
National Lamp Works of General Electric Company,
Nela Park, Cleveland, Ohio.

Armor-plate. ANON. (*The Times* (London) *Engineering Supplement,* No. 500, June 30, 1916.)—The idea of using armor-plate as a protection against gun fire arose long before it was actually put into practice. It bore at first two aspects, the protection of shore batteries on the one hand, and of floating batteries on the other. The first was proposed and tested by Major-General Ford at Woolwich in 1827. A granite wall 7 feet thick was faced with two layers of iron bars 1¼ inches square, disposed vertically and horizontally; this defence was destroyed by shots from a 24-pounder gun. In America, Messrs. Stevens, of Hoboken, made some tests with 4-inch wrought-iron plates. In England, experiments were carried on in the dock-yards from 1846 to 1856, and in one series a 4½-inch wrought-iron plate was supported by a timber backing. In France, floating batteries propelled by steam were built for service in the Baltic during the Crimean War. The plates used were 4½ inches thick, 3 feet long, and 20 inches wide, and they were able to resist the Russian 32-pounders. Then came (1855) the first Armstrong breech-loading gun, which heralded a new era in artillery and the beginning of the intense struggle between the penetrative power of guns and the resistance of armor.

The first armored ship, as distinct from floating batteries, was the French *Gloire* (1855), having iron armor-plates 4¾inches thick. The plates were rolled at Creusot by Messrs. Schneider, who in due course (1876) also made the first steel armor-plates. At the same time that the *Gloire* was being completed in France, the famous *Warrior* was being built at Blackwall with iron-armor-plates 4½ inches thick. When the Palliser chilled point projectiles were introduced (1863), wrought-iron armor developed in the only direction it could take—an increase in the thickness of the plates, which in successive stages advanced from 4½ inches in the *Warrior* (1860) to 24 inches in the *Inflexible* (1880). The *Repulse* was provided with 6-inch armor in 1870, and the *Thunderer* with 12-inch in 1877.

When the *Inflexible* armor of 24 inches was fitted, it was necessarily made up of two thicknesses.

The beginning of the substitution of steel armor-plate for that of wrought iron dates from about 1878. In 1877, tests had been made by Whitworth and Cammell. Generally, the steel plates arrested the projectiles but suffered badly, being more or less cracked and shattered. The suggestion was, in consequence, put forward that the best solution might be found in a hard steel facing backed up by wrought iron, which would hold the fractured parts together. A plate with a hard steel face welded to a soft iron back, developed independently by Messrs. John Brown and Messrs. Cammell, embodied this idea. It was used in the British Navy for several years, and was, in fact, unrivalled until the advent of the solid steel plates produced at Creusot by the Schneider firm, who were the first to employ nickel to increase the tenacity of the steel. The modern Harvey, Schneider, and Krupp plates evolved since 1891 are developments in imparting to highly resisting solid steel plate a surface of intense hardness by cementation and subsequent quenching.

A Semi-floating Highway Bridge. ANON. (*Engineering Record*, vol. 74, No. 6, August 5, 1916.)—During the construction of a bridge across Costiac Creek, in Los Angeles County, California, highway traffic has had to ford the stream at a point where the depth is usually sufficient to submerge the carburetor of the average car. Teams have therefore been maintained at the crossing by the county to tow automobiles across. This procedure, however, usually caused considerable trouble in getting the engine started again, and it was recently determined to try a better method.

The stream has a sandy bottom, and the depth is fairly uniform, so it was decided to build a plank road in sections, and hold it in place by cables in such a way that a good surface would be continuous across the ford. By this plan the effective depth of the water would be decreased, not only by the thickness of the plank and stringers, but also by the amount which tires would otherwise sink into the soft, sandy bottom. As a matter of fact, the heavy plank units are so buoyant that light cars pass over them at fairly high speeds with practically dry tires, and, even at slow speeds, heavy cars can safely cross under their own power. After being built on shore and floated to place, the sections were held together by a ¾-inch cable, threaded through eyebolts in each section. This cable was attached at 12-foot intervals, by means of ½-inch cables, to a ⅞-inch cable stretched across, 25 feet above the plank sections, and drawn sufficiently taut to hold it 4 feet above high water. On the down-stream sides the sections were wired together by strands of No. 12 galvanized wire. At each end of the ford 4-foot sections were left with free ends resting on shore. The total length of the crossing is about 104 feet. The bridge was completed in two days, at a cost of $17.50 for labor and $126 for material and transportation.

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Greatest World Petroleum Output. ANON. (*U. S. Geological Survey Press Bulletin,* No. 284, August, 1916.)—That 1915 was the most successful year of production in the history of the petroleum industry is shown by statistics just compiled under the supervision of J. D. Northrop, of the U. S. Geological Survey, Department of the Interior.

The total quantity of crude petroleum entering the world's markets in 1915, which amounted to 426,892,673 barrels, exceeds the former record, established in 1914, by 28,194,307 barrels, or 7 per cent.

The bulk of the increase in 1915 came from the United States and Mexico, though Russia, Argentina, and Japan recorded significant gains.

CURRENT TOPICS.

Contact Resistance of Metal Electrodes. N. K. CHANEY. (*Proceedings of the American Electrochemical Society*, April 27–29, 1916.)—In some unpublished work the writer has shown that under certain conditions a high "contact resistance" exists between the surface of an electrode of sheet zinc and the electrolyte. The "contact resistance" between zinc and ammonium chloride is a secondary development, occurring with measurable rapidity after the immersion of the zinc in the electrolyte. At the instant of immersion it is very small. It may rise to values of 200 to 400 ohms per square inch (1250 to 2500 per square centimetre) of electrode surface. It forms the principal part of the internal resistance of dry cells at low-current drains, and, as determined by measurements upon the latter, it has a high temperature coefficient, decreasing to one-tenth of its value with a temperature rise from 0° to 45° C. This is the contact resistance of the zinc electrode which was measured by Carhardt in his resistance measurements upon the early Gassner dry cells which caused the rapid rise in his resistance curves at low-current densities. With densities above certain low limiting values, it is lessened or temporarily destroyed, being practically unaffected by currents of less than 1 milliampère per 50 square inches (315 sq. cm.) of electrode surface, even if continued for a considerable time. At higher current densities it begins to rapidly decrease, and becomes negligible at current densities of about 1 ampère per 50 square inches. Upon open circuit the resistance again slowly rises toward its initial value. It is destroyed or very greatly reduced by chemical treatment of the zinc surface; *e.g.*, by corrosion with dilute sulphuric acid.

An explanation of these phenomena is based upon the supposed existence of a hydrogen film upon the electrode surface, discharged there by the local action between the zinc and the electrolyte. This is supported by a considerable amount of experimental evidence in which it is shown that the predicted behavior of such a hydrogen film under selected conditions is in agreement with the observed behavior of the contact resistance. These facts must have a significant relation to the theories of over-voltage phenomena and kindred problems bearing on the nature of the equilibria between the electrode surfaces and the electrolyte.

Electrolytic Coating of Silvered Mirrors. ANON. (*Revue General des Sciences*, vol. 27, No. 12, June 30, 1916.)—The old method of coating mirrors by the mercury process is a long, tedious, and unwholesome operation which has been nearly universally re-

placed by silvering. The latter method is, however, by no means perfect; the very thin film deposited by reduction of a solution of nitrate of silver is neither as white nor as brilliant as that of tin amalgam; it is deficient in strength, being detached by the slightest friction, and tarnished on exposure to sulphurous fumes. These faults are only very imperfectly overcome by a backing of varnish, of itself often a source of deterioration. Long ago an electrolytic deposit had been considered as a substitute, but experiments in this field yielded only mediocre results, whose irregularity was mainly due to the extreme thinness of the silver coating. Indeed, in the electrolytic method, it is this metallic film which consitutes the kathode, whose very minute cross-section is a poor conductor. When the contact is made around the periphery of the silvered glass, the electrolytic deposit takes place almost entirely in its immediate vicinity, and at points remote from the edges the thickness of the deposit diminishes rapidly, so that at the centre there is scarcely any deposit.

This drawback has been cleverly overcome by Delere, Gresy, and Pascalis, whose method is in actual use in Paris by the Compagnie des Glaces de Saint-Gobain. This process, styled "silvered protector" (French patent No. 444,710), consists in multiplying the number of current-carrying points of contact on the silver kathode by means of flexibly supported metallic combs. These combs have brass teeth, to each of which is attached a globule of tin, a soft metal which avoids scratching the silvering. All parts of the electrode immersed in the electrolyte are covered with an insulating layer of paraffin, with the exception of the points in contact with the silvering. The anodes consist of bands of pure copper supported between the contact points. The mirror to be coated is laid, silvered side up, in a shallow tray containing the electrolyte, the latter being kept of uniform strength by forced circulation. During the plating the current is interrupted every few minutes and the contact points shifted a short distance. The electrolytic action is thus uniformly distributed over the entire surface, resulting in a very homogeneous deposit of copper. Mirrors so protected resist the action of sulphurous fumes under the most unfavorable conditions and possess the unexpected advantage of increased reflecting power.

New Measuring Flume. ANON. (*Engineering News*, vol. 76, No. 6, August 10, 1916.)—Experiments made in the hydraulic laboratory at Fort Collins, Colo., by the United States Department of Agriculture have resulted in the development of a measuring flume which the experimenters believe promises to overcome the chief difficulties experienced in measuring water for irrigation purposes. The action of the device depends upon the adaptation of the Venturi principle to the flow of water in an open channel. The vertical sides of the flume for a short distance converge to a throat, and from that point diverge to its normal breadth, making it in

plan similar in contour to a Venturi tube. Gauge boxes are provided at the throat and at a point down stream for a measurement of the head.

The laboratory tests thus far made indicate that the device is quite accurate in its measurements. The Venturi flume is inexpensive and easily constructed and maintained. It automatically takes care of the velocity of approach and requires but little loss of head in the ditch. The increased velocity in the throat greatly reduces the danger of trouble from silt, sand, aquatic growth, or floating trash. The discharge through the flume is dependent upon the depth of water in the throat or the diverging section, as well as upon the difference of depths.

The Principles of Filtration. D. R. SPERRY. (*Metallurgical and Chemical Engineering,* vol. xv, No. 4, August 15, 1916.)—The process of filtration consists in separating the solids from a mixture of solids and liquid by causing the liquid to flow away from the solids through a porous mass, the openings of which are too small to allow passage of the solids. The porous mass, called the filtering medium, is composed of two parts: that which was provided in order that filtration might begin, called the filter-base, and that which was formed during filtration, called cake, consisting of solids which were too large to pass through the openings of the porous mass. At the beginning of filtration the filter-base comprises the entire filtering medium. As the flow proceeds the solids are deposited upon the filter-base, and the filtering medium now consists of the filter-base and deposited solids or cake. The flow of liquid through the porous mass and the building up of the porous mass are constantly changing because the liquid, as it flows into the cake, is continually leaving its solids behind, thus constantly increasing the thickness of the porous mass, while, simultaneously with this action, the liquid is continually decreasing its own rate of flow, due to the increasing thickness of solids through which it has to pass.

It is evident that if an expression can be derived showing the relation between the flow of the liquid and the building up of the porous cake and the laws of each determined, the two can be combined in a known relation, thus expressing the fundamental laws of filtration. Such an analysis of the two processes and a determination of their relationship leads to a formula for the total quantity of filtrate discharged in terms of time, pressure, and other known physical quantities of the materials employed.

The Dry Powder Fire Extinguisher. ANON. (*Quarterly of the National Fire Protection Association,* vol. 10, No. 1, July, 1916.)—Recent analyses made for the British Government show that dry powder fire extinguishers generally contain as their main constituent bicarbonate of soda, the amount of which varies from about 46 per cent. to 56 per cent. in the different samples examined. It is

true that bicarbonate of soda, on heating, gives off a certain quantity of carbon dioxide, but, in the opinion of the investigating committee, it is doubtful if the quantity generated has a materially effective influence on the action of the powder as an extinguisher, except possibly in cases of small fires of a special nature and limited extent. Water is far more effective than dry powder, the wetting of the surrounding material preventing the spread of the fire and thus confining its area. In the application of water, experiment showed that a given volume of water applied as a jet was decidedly more effective than the same amount applied by buckets. If the whole of the carbonic acid available on heating were given off suddenly, immediately the powder is strewn on the fire, approximately one cubic foot of gas would be formed for each pound of powder used. The smothering effect of this quantity of gas may be contrasted with that of the enormously larger volume of steam which would be generated by one pound of water, which gives over 25 cubic feet of steam at atmospheric pressure.

Water Power Could Not Displace Steam. E. WHITE. (*Coal Age*, vol. 10, No. 2, August 12, 1916.)—The town of Macon, Mo., is built over a bed of bituminous coal which ranges from 22 to 26 inches in thickness. Any resident in the city could sink a shaft in his back yard from 80 to 100 feet deep and be independent of the coal dealer.

When the Keokuk Power Company began reaching out for business, a subcontracting firm sent representatives to Macon with an offer to furnish the city and private consumers with electrical energy at 3½ cents per kilowatt-hour. This offer was also extended to neighboring towns. The section which the water power company proposed to supply was about 130 miles from the dam. The superintendent of the municipal power plant at Macon made some comparisons. He found that with coal-produced power he could undersell his big competitor over on the Mississippi River. With coal at $1.39 a ton in the bin and a plant of 400 horse-power, composed of two engines direct connected with generators, he discovered that, based on water-power rates, the coal-produced energy was saving the city $400 a month. He then went after the outside business in the same way that the hydro-electric company is doing, and closed contracts with the neighboring towns of Bevier and Callao for transmission of electric power. After a year's operation as a central power station, the Macon municipal plant has been able to show an annual profit of $5000 above operating expenses.

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